Beam Cooling

Søren Pape Møller, Aarhus University, Denmark

- Introduction to cooling, temperature, phase space and Liouville
- Stochastic cooling
- Electron cooling
- Laser cooling
- Radiation damping
- Ionisation and other cooling

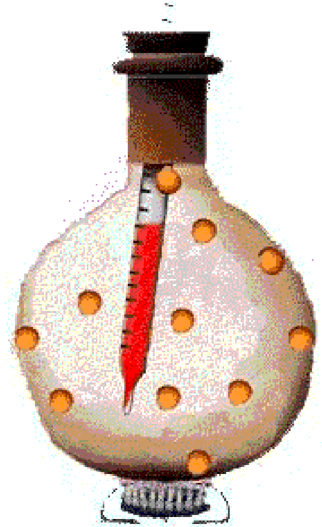
cooling is <u>not</u>:
collimation (loss of particles)
adiabatic damping

Beam cooling

- Since beamcooling is ”slow”, it is mostly used in storage rings;
- however, ionisation and ”stochastic cooling” has been or will be used for e.g. for muons

Introduction

What is cooling? What is Temperature?



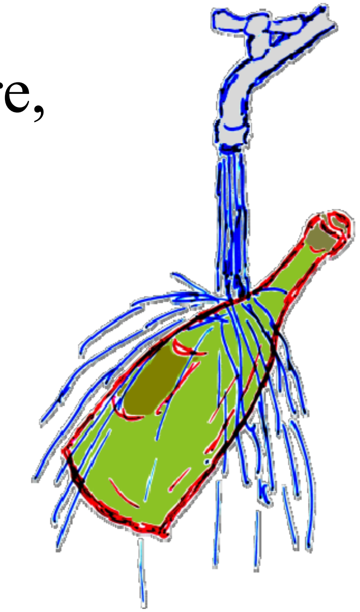
$$(\tfrac{3}{2}k)T_{\perp//} = \tfrac{1}{2}m\langle\vec{v}^2_{\perp//}\rangle$$

v is the velocity relative to the reference particle moving with the average ion velocity. (internal temperature)

Temperature is a measure of the disordered motion.

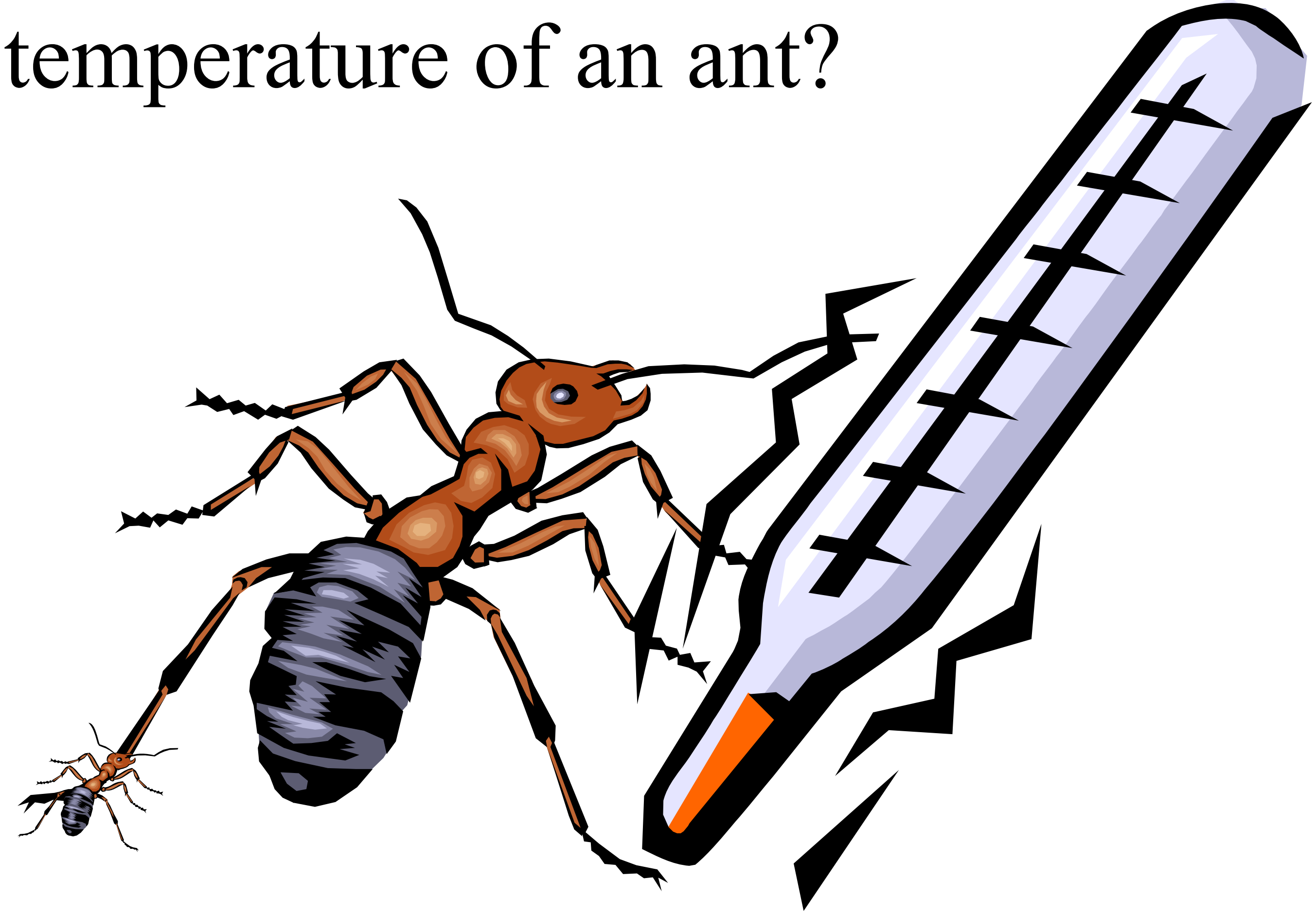
Cooling is hence a reduction of the temperature, i.e. of the disordered motion.

Clearly, other parts of the total system will get warmer.



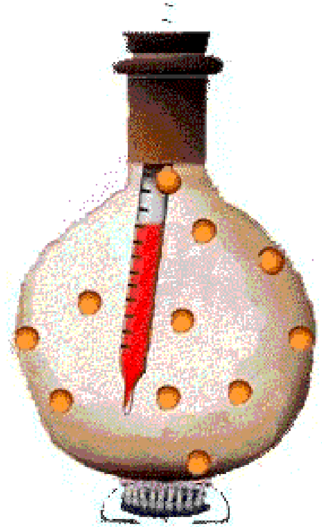
My old thermodynamics teacher

- How do you measure the temperature of an ant?



Introduction

What is cooling? What is Temperature?



$$(\tfrac{3}{2}k)T_{\perp//} = \tfrac{1}{2}m\langle \vec{v}^{\,2}_{\perp//}\rangle$$

v is the velocity relative to the reference particle moving with the average ion velocity.
Temperature is a measure of the disordered motion.

In an accelerator

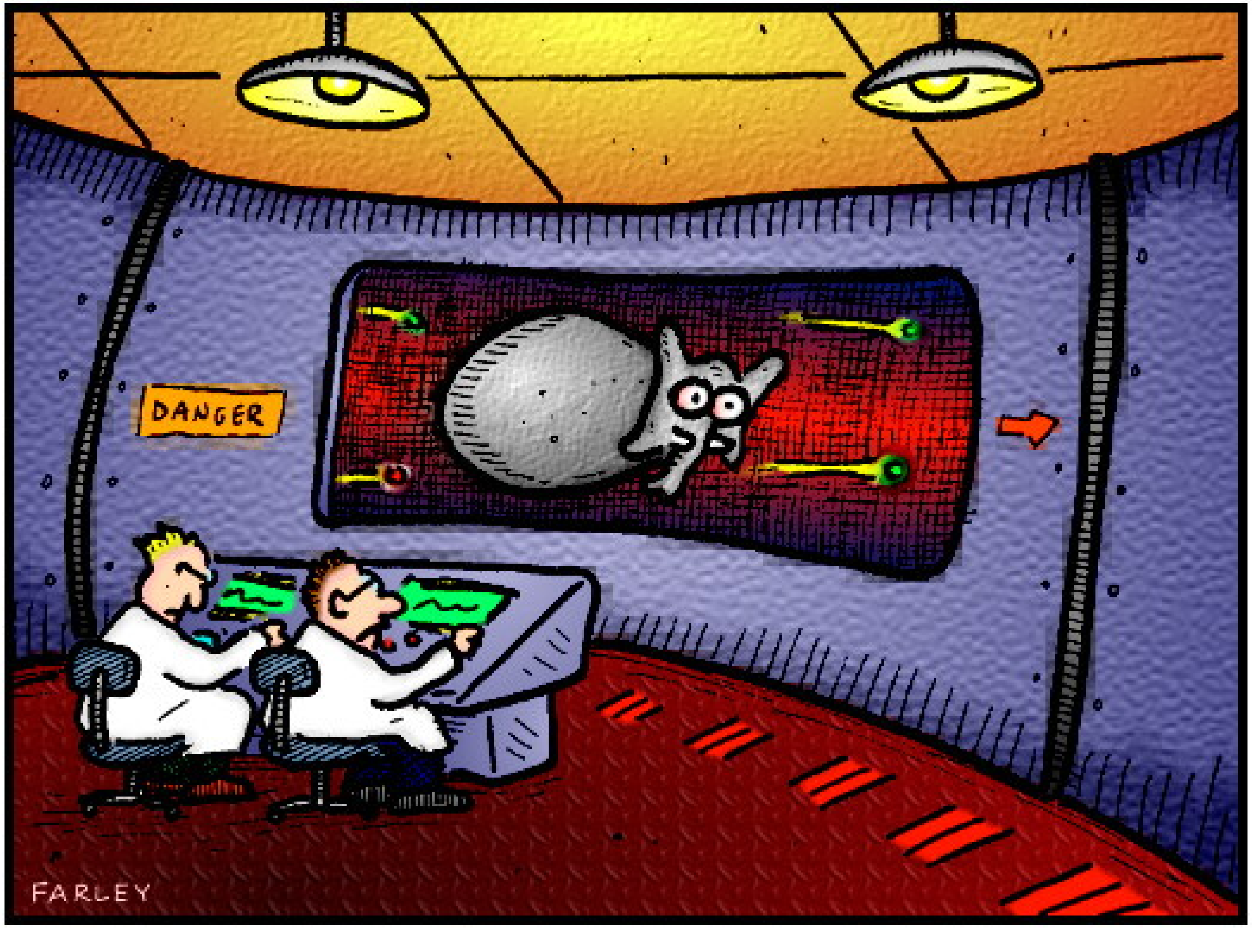
$$T_{//} = Mc^2\beta^2\langle \Delta p / p\rangle^2$$

$$T_{\perp} = Mc^2\beta^2\gamma^2\varepsilon\left(\frac{1}{\langle \beta_H\rangle} + \frac{1}{\langle \beta_V\rangle}\right)$$

Why beam cooling?

DOCTOR FUN

11 May 94



Deep within the atomic supercollider, the search continues for the elusive elephantino.

Why beam cooling?

Improve beam quality

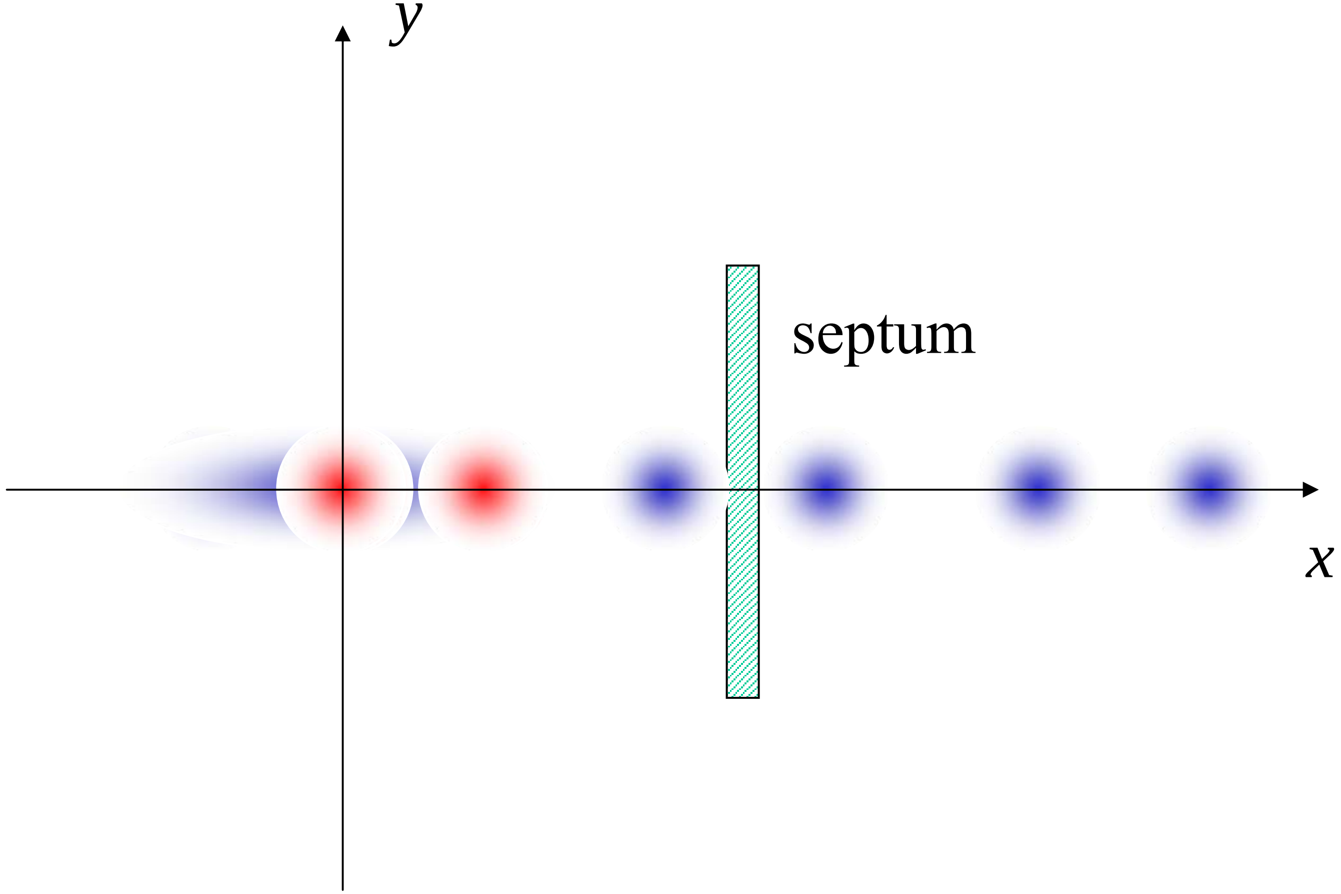
- beam size, emittance
- energy spread
- intensity of beam, accumulation, stacking
- lifetime of beam

Counteract degradation of beam quality

due to interaction of beam particles with

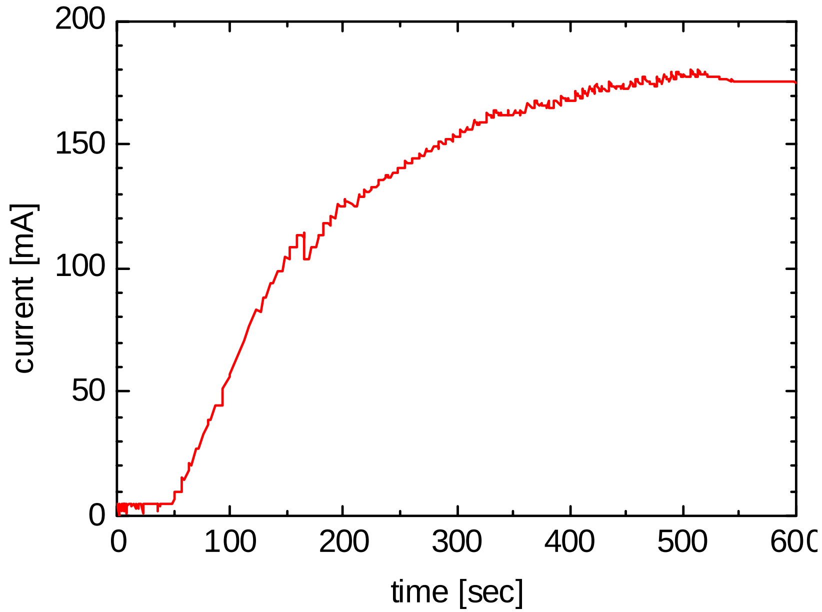
- other particles (intrabeam scattering)
- rest-gas (internal targets)
- non-ideal fields, resonances, instabilities
  injection errors

Stacking by cooling



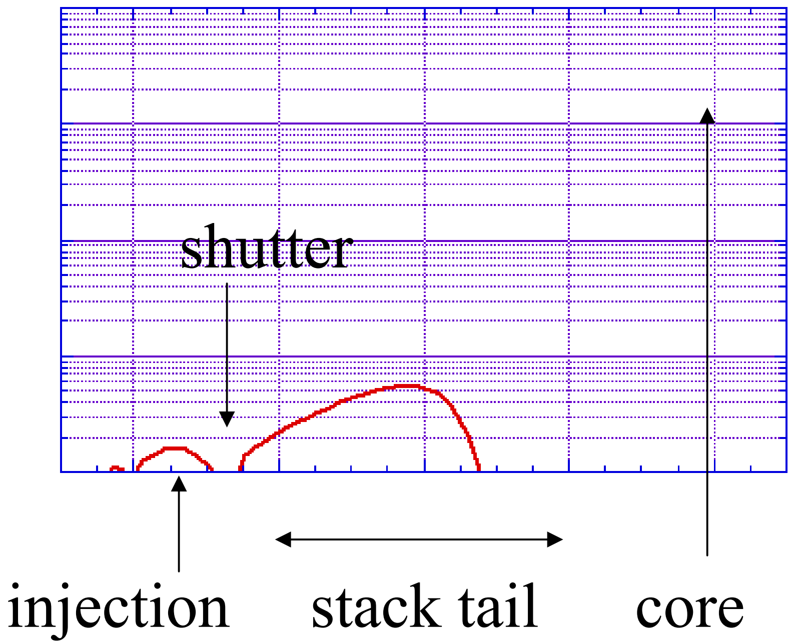
Stacking by cooling 2

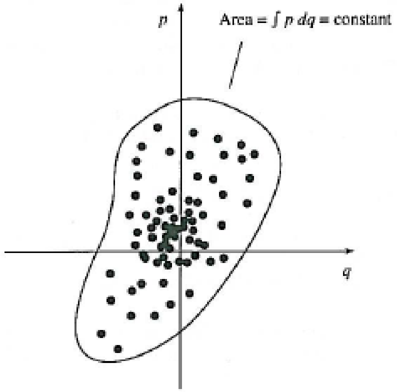
ASTRID SR source:
~200 mA accumulated
from many injections
of ~5 mA



Fermilab antiproton
accumulator
stacking for 1 hour

10^8/2 sec pbar at 8 GeV





Liouville formelt

Et system bestående af N partikler beskrives i $6N$ dimensionalt faserum.

Hvis partiklerne ikke vekselvirker kan systemet beskrives som N partikler

i 6 dimensionalt faserum med såkaldte konjugerede koordinater $\vec{q}, \vec{p}$,

$p_i = \partial L / \partial q_i$, hvor $L(q, \dot{q}, t) \equiv T - U$ er Lagrangefunktionen

F.eks. x,y,z og de tilhørende impulser p_x, p_y, p_z

Hamiltonfunktion $H = H(q, p, t) \equiv \sum p_i \dot{q}_i - L$

Hamiltons ligninger siger $\dot{p} = -\partial H / \partial q + Q \quad \dot{q} = \partial H / \partial p$, hvor $\partial H / \partial q$ er den

konservative eller Hamiltonske del, der kan udledes fra et potential,

og Q er ikke Hamiltonske kræfter som friktion etc.

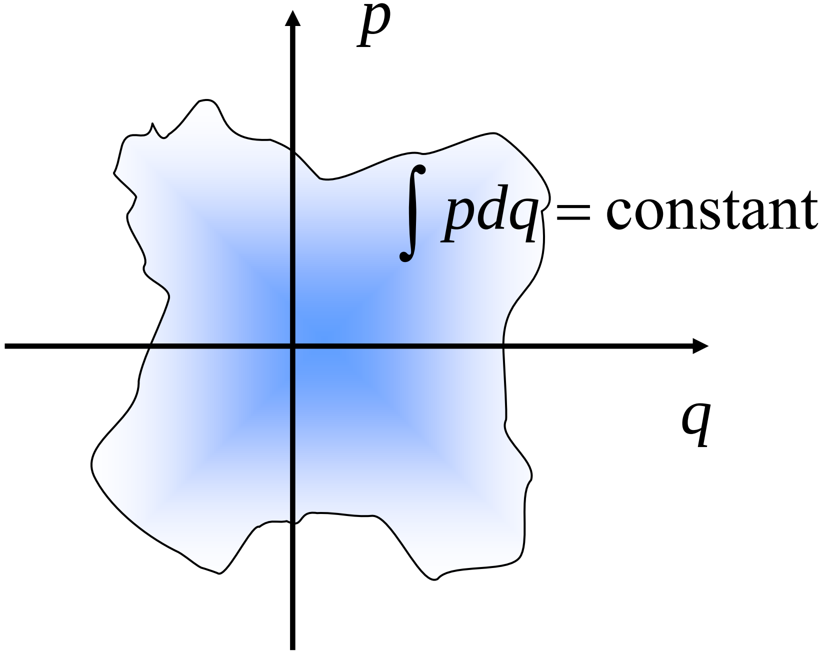
Kontinuitetetsligning $\dfrac{d\rho}{dt} = -\rho \sum \dfrac{\partial Q_i}{\partial p_i} \Rightarrow$ Liouville for konservative kræfter

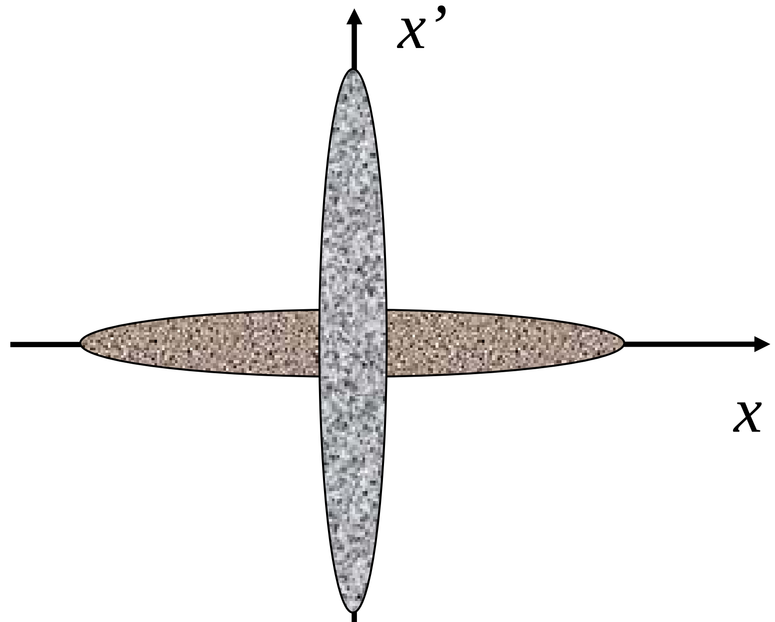
$d\rho/dt = 0 \Rightarrow \rho =$ konstant

Phase space and Liouville

Liouville: For hamiltonian systems, the phase space density is constant (when measured along a trajectory)
The phase space volume (emittance) is conserved

Often the two transverse and the longitudinal degrees of freedom are decoupled





Quadrupole focusing

Phase space, Liouville and cooling

Liouvilles theorem means that cooling is <u>not</u> possible for Hamiltonian systems, that is systems with forces that can be derived from potentials.
In addition particles cannot be injected into already filled areas of Phase space.
All you can do is to change the form of phase space.

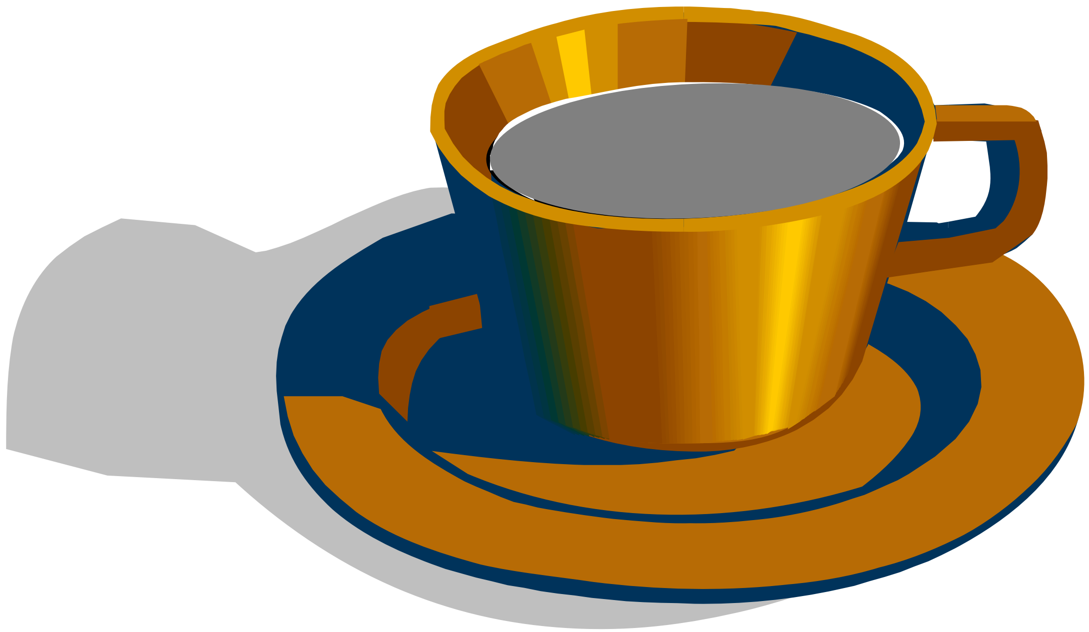
<u>However</u>, with velocity-dependent forces

drag, friction (dissipative) forces

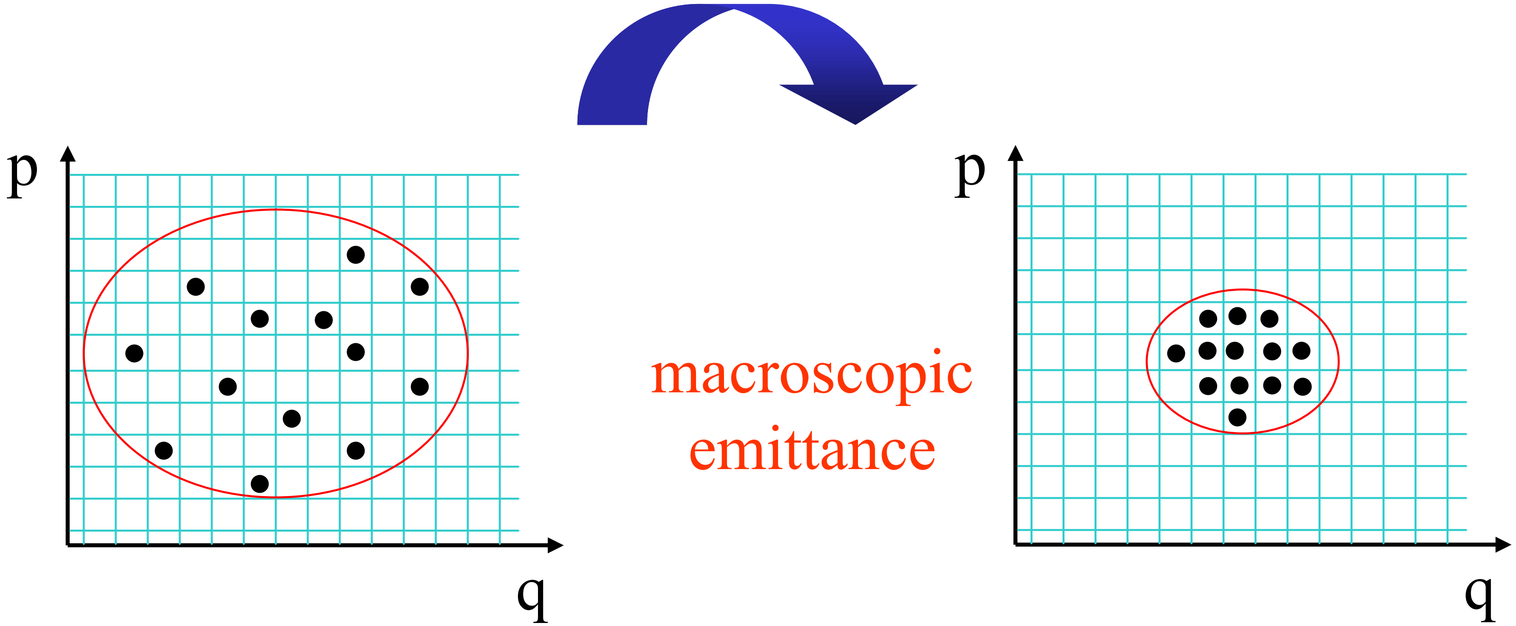
electron, radiation, Laser, ionisation cooling

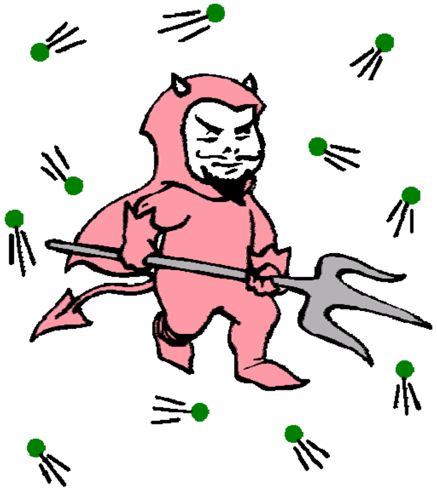
cooling is indeed possible!!

Coffee, cream, Liouville and Stochastic cooling



Stochastic cooling principle

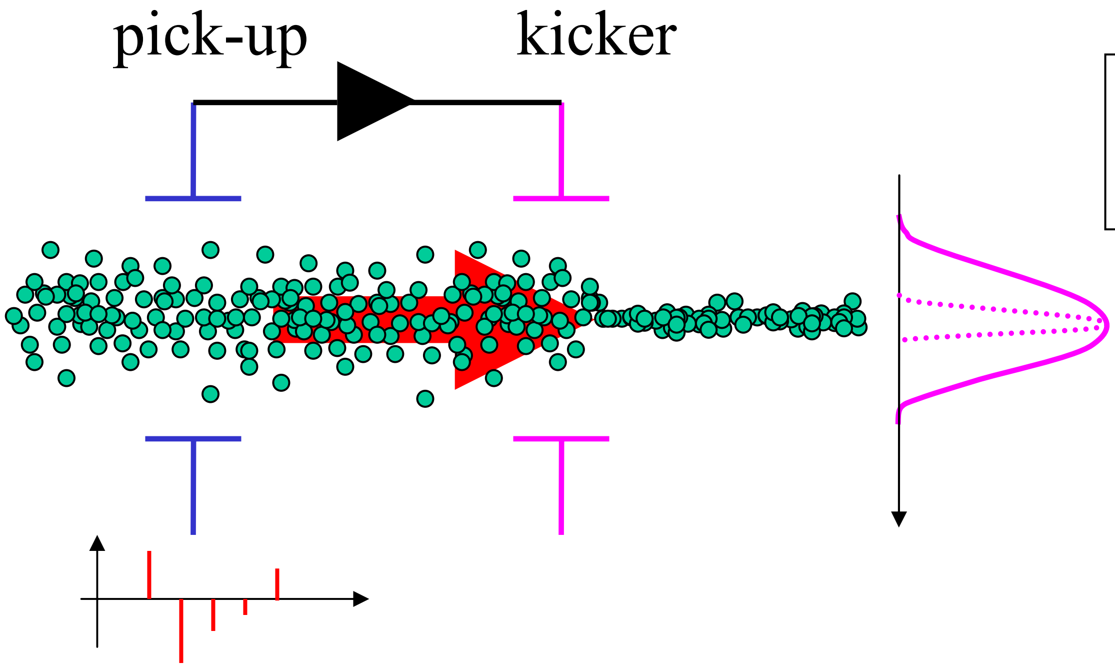




Maxwells demon

Stochastic cooling

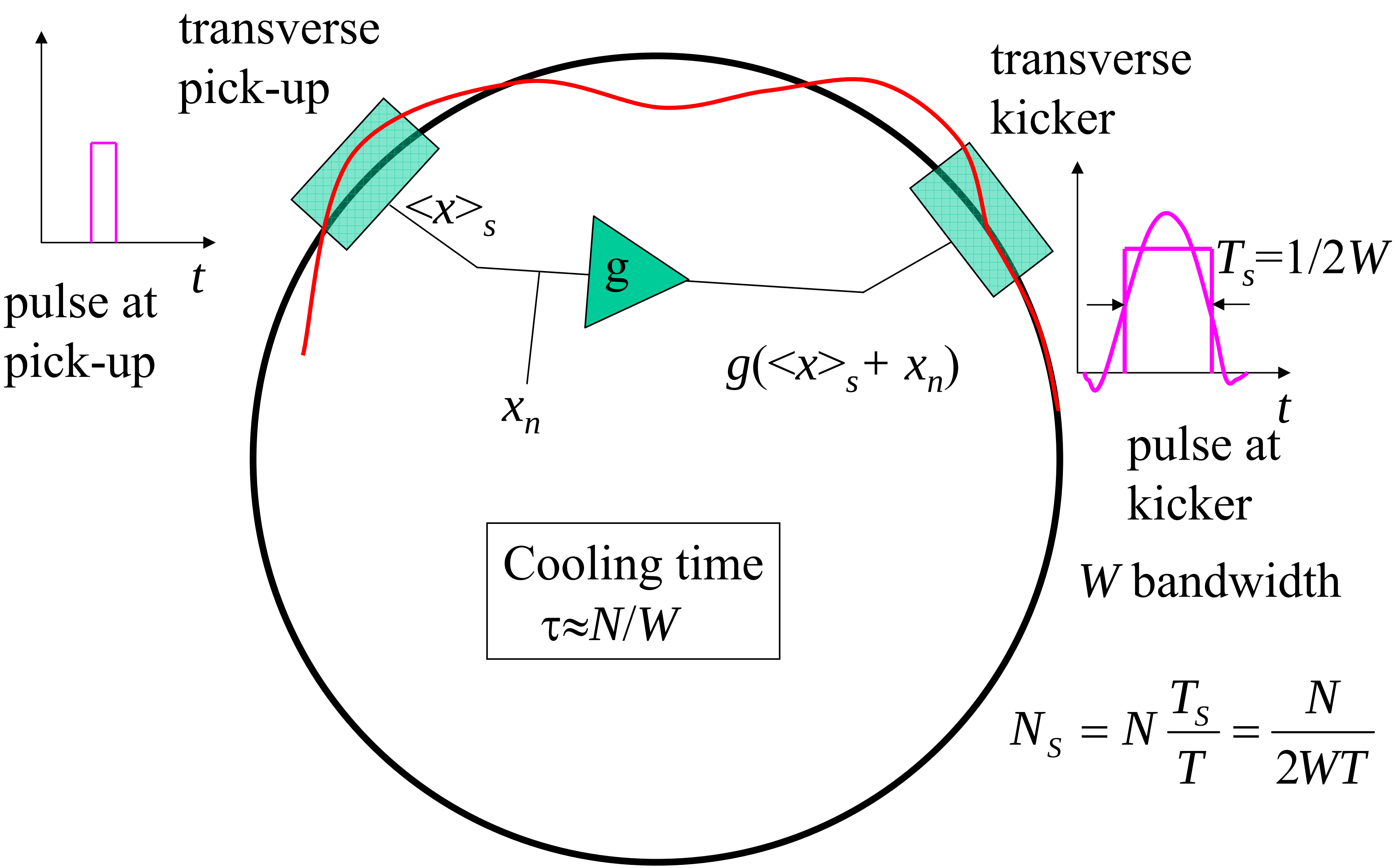
Liouville: Cooling is not possible with electromagnetic forces deflecting the particles (continous fluid, og N=∞).
When single particles can be observed, and a corresponding correction applied, cooling is possible!
This is the secret of stochastic cooling!



$N=10^8$, $\sigma=5$mm
$\sigma/\sqrt{N}=0.5\mu$m

In reality $W < \infty$

Stochastic cooling

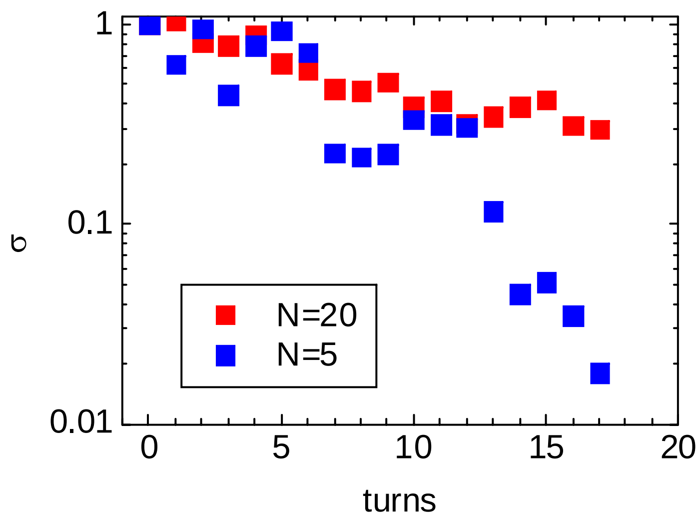


W bandwidth

$$N_S = N\frac{T_S}{T} = \frac{N}{2WT}$$

Stochastic cooling exercise

1) Ask for 5 random numbers with $\langle x \rangle = 0$ and $\sigma = 1$
2) Find actual $\langle x \rangle$ (in general $\langle x \rangle \neq 0$)
3) Subtract error in mean to restore mean to zero
4) Calculate new σ
5) Goto 1)
6) Watch σ as function of time
7) What is the cooling time?
8) Include electronical noise!



Cooling Time

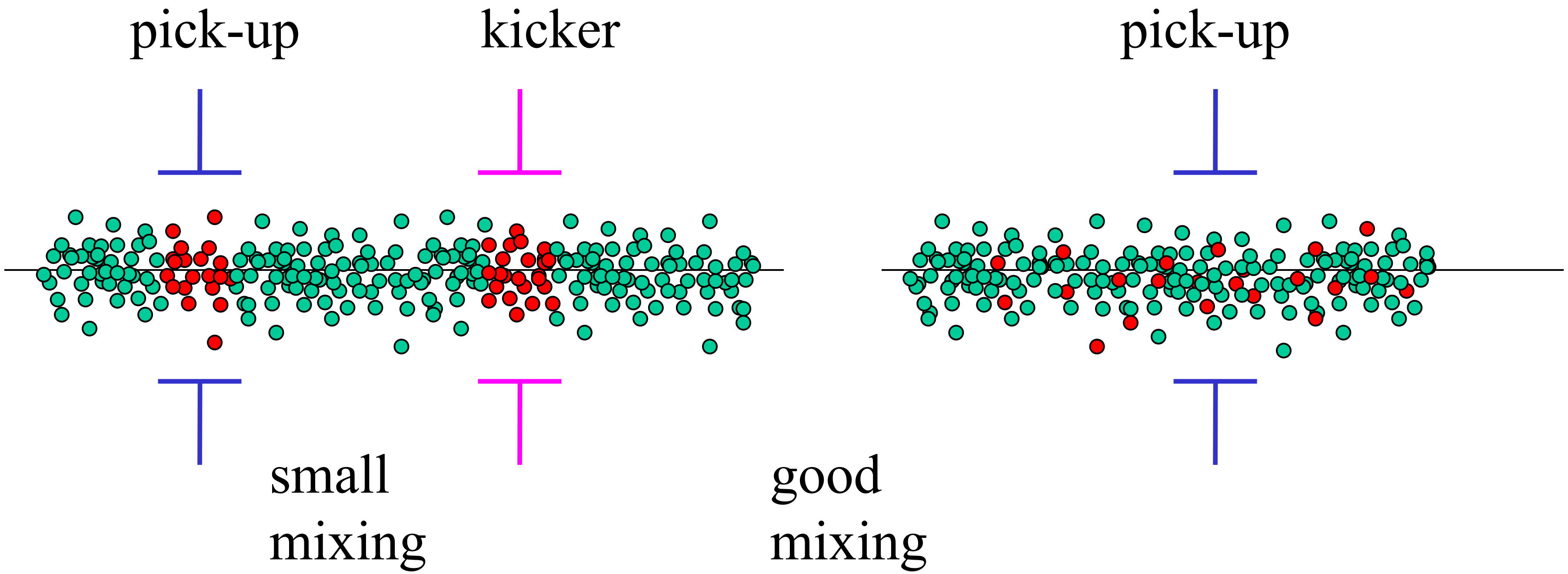
mixing

$$\frac{1}{\tau} = \frac{gW}{N}\left[1 - \frac{g}{2}(\Gamma + \upsilon)\right]$$

noise/signal-ratio

optimum gain $g = 1/(\Gamma + \upsilon) < 1$

optimum cooling time $\quad \frac{1}{\tau} = \frac{W}{N(\Gamma + \upsilon)}$



Cooling time 2

$$\frac{1}{\tau} = \frac{gW}{N}\left[1 - \frac{g}{2}(\Gamma + \upsilon)\right]$$

optimum gain $\quad g = 1/(\Gamma + \upsilon) < 1$

optimum cooling time $\quad \frac{1}{\tau} = \frac{W}{N(\Gamma + \upsilon)}$

$\tau \propto N$

Decrease gain as cooling proceeds

Good mixing, $\Gamma = 1$, by designing storage ring so

$\eta = \partial(\Delta T/T)/\partial(\Delta p/p)$ is large. However small mixing PU$\rightarrow$K

Large bandwidth ($W >$ GHz, $N_s \sim 10^{-3} N$)

Weak dependence on energy

Z dependence in υ

Stochastic cooling

Betatron cooling: 2 systems (hor. and vert.)

dist. PU $\rightarrow$ kicker = odd number of $\lambda/4$

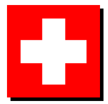
Momentum cooling:

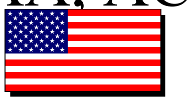
acc. gap instead of transverse kicker

(i) PU in high-dispersion region $\Delta x/x = D\ \Delta p/p$

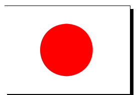
(ii) detect $\Delta f/f = \eta\ \Delta p/p$ and correct $\Delta p/p$

Stochastic cooling facilities:

ISR (1977), ICE, AA, AC, LEAR, AD @ CERN 

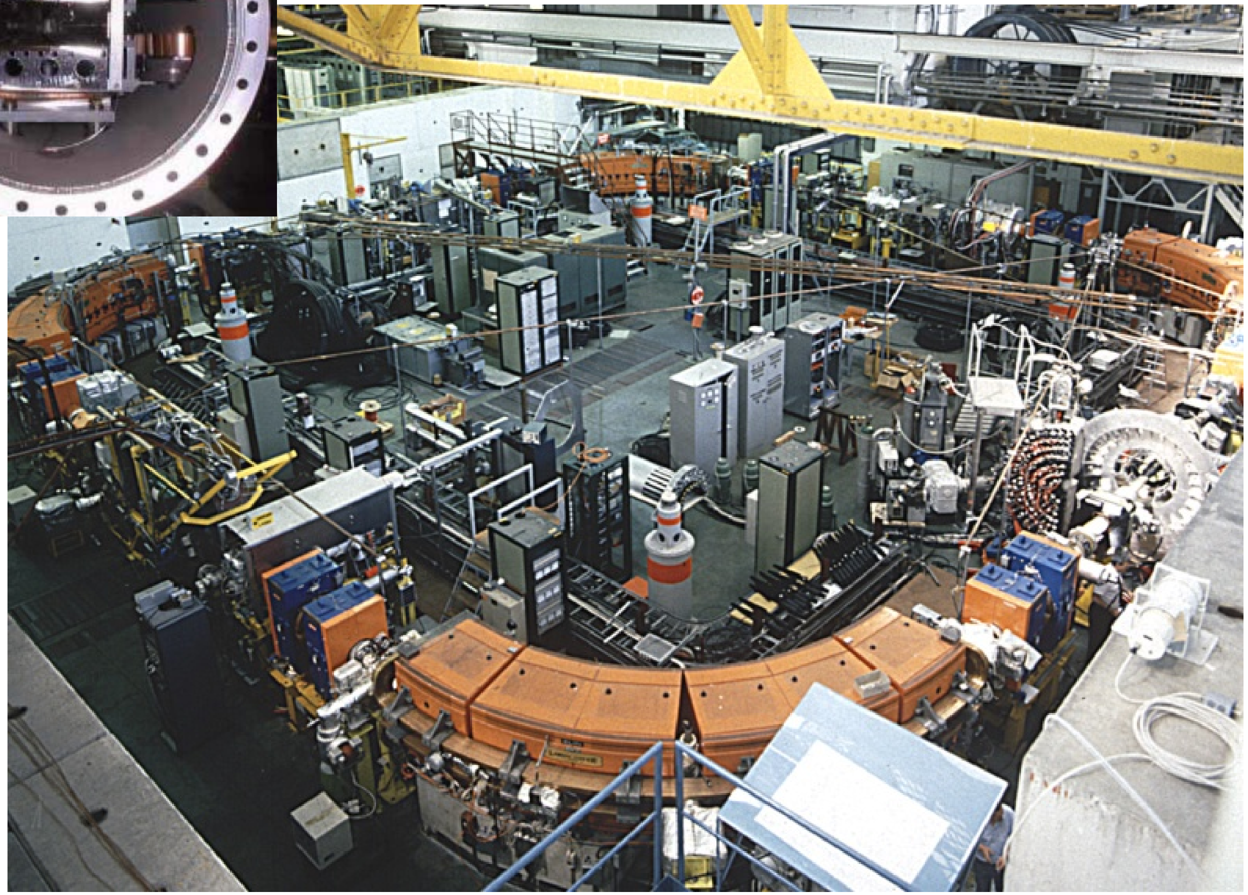


Fermilab

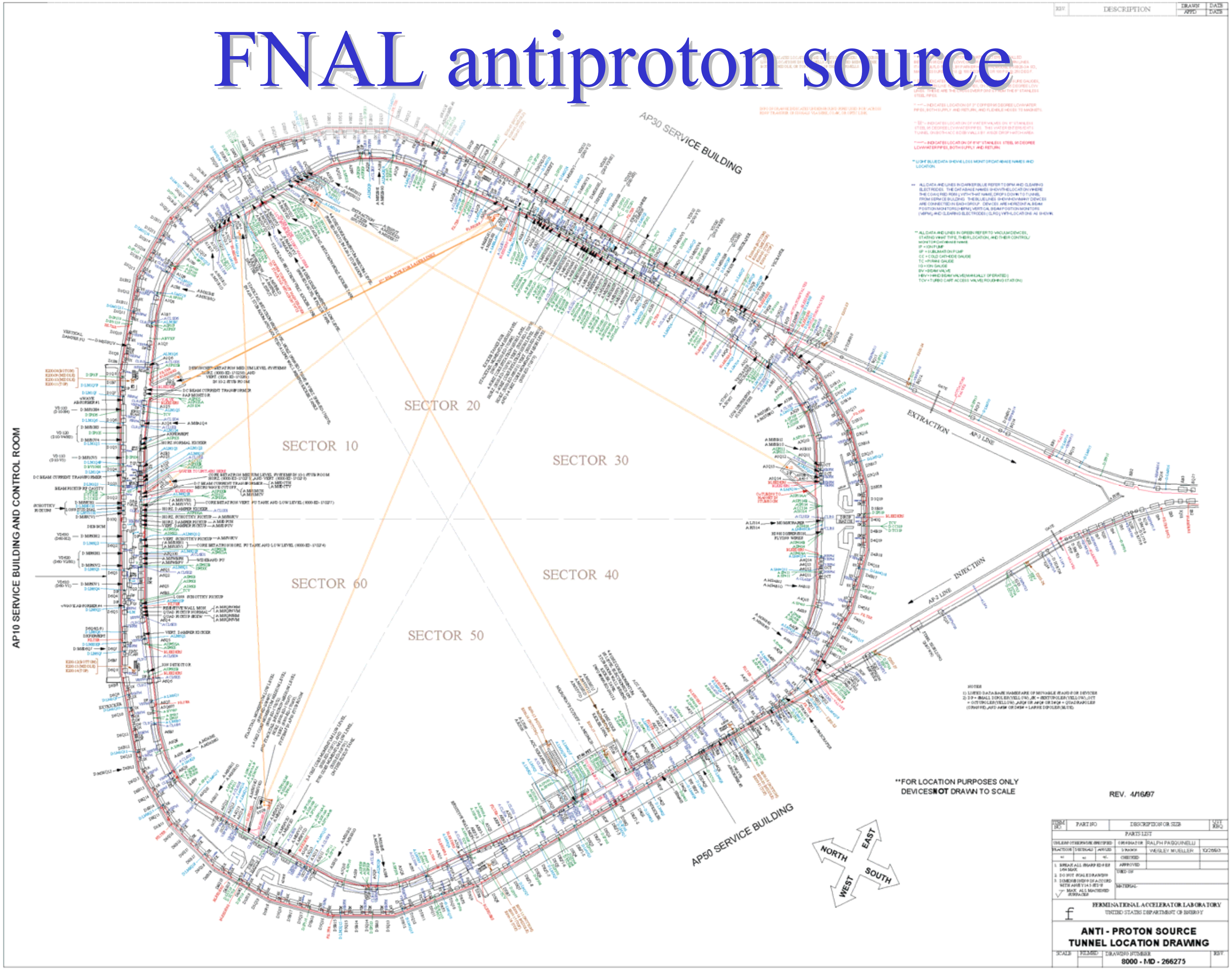
TARN 

COSY, GSI 

Stochastic Cooling

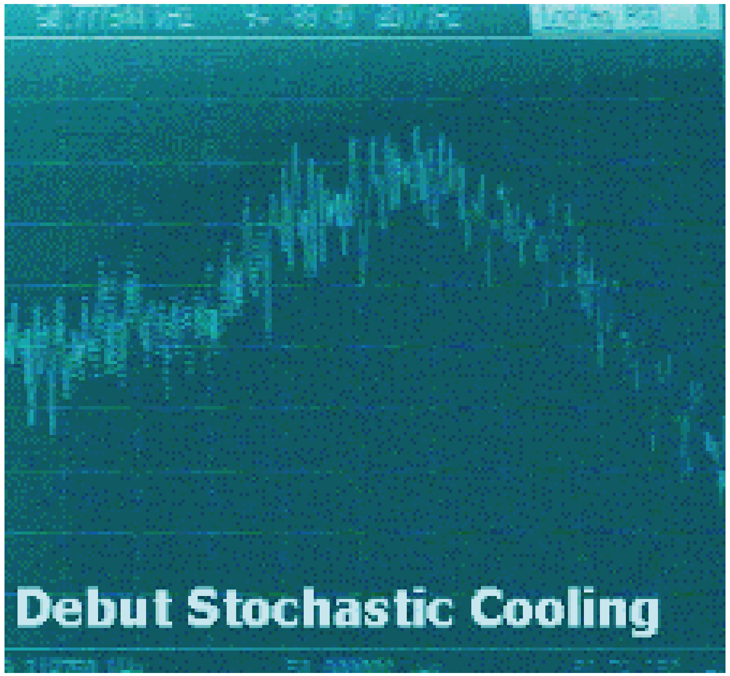


FNAL antiproton source



Stochastic Cooling

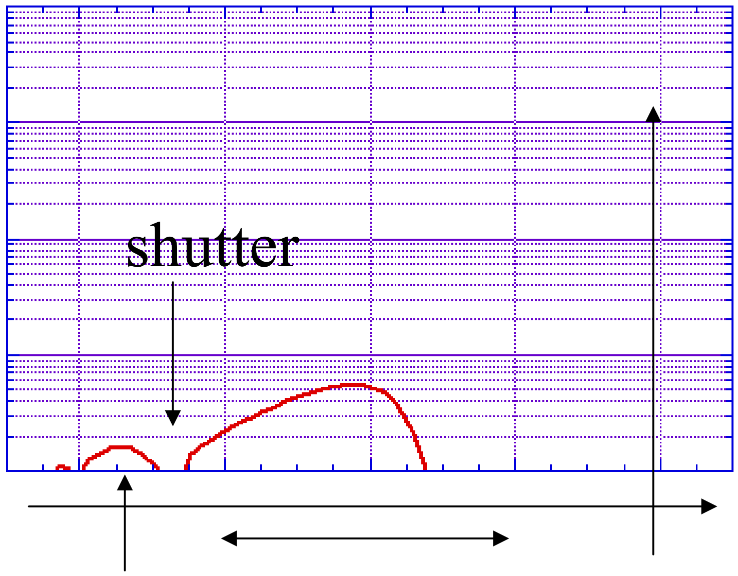
AD at CERN



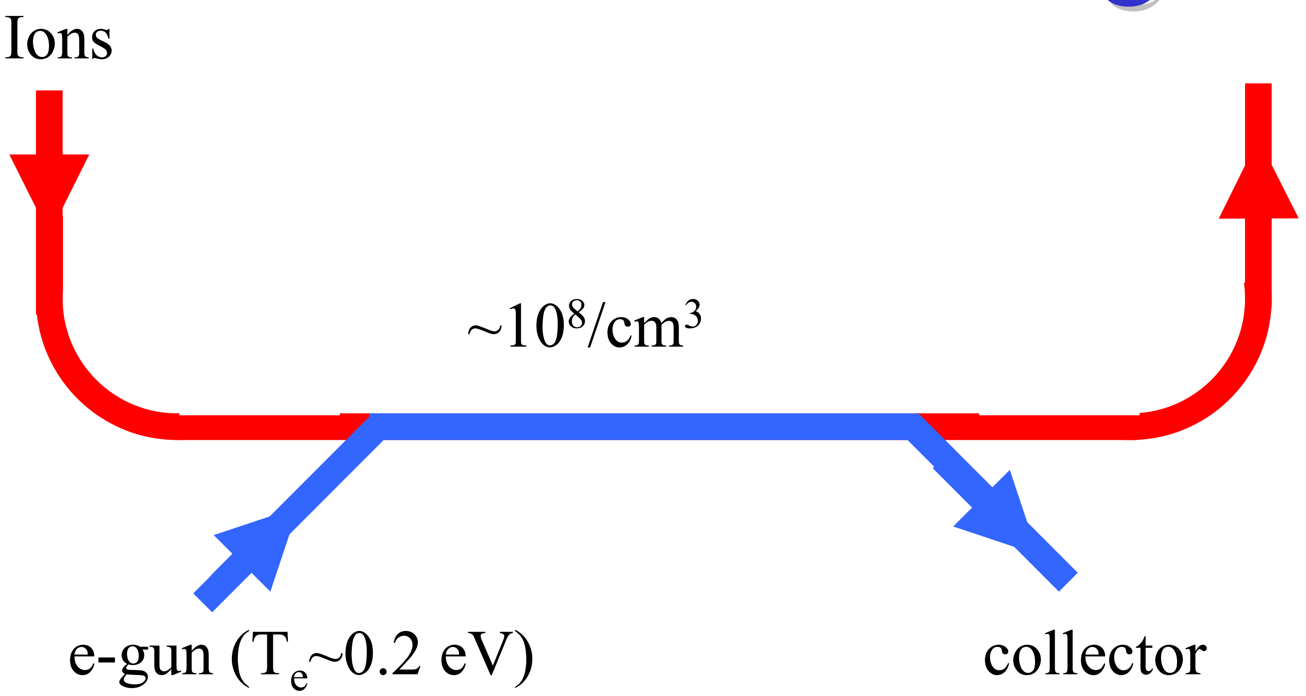
$\Delta p/p$ $(\Delta f/f)$

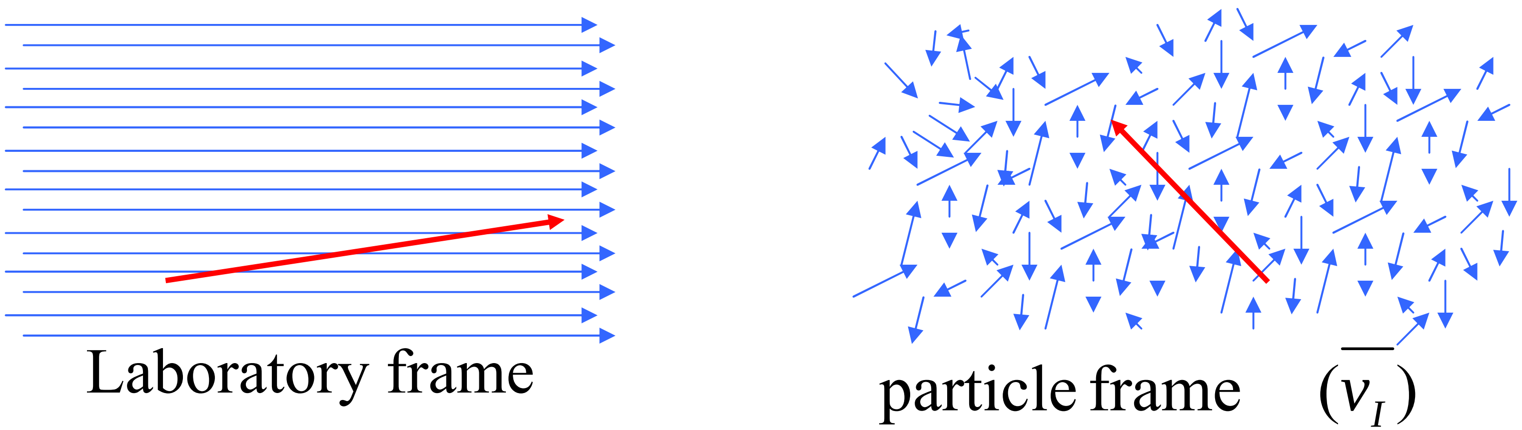
Fermilab antiproton accumulator stacking for 1 hour

10^8/2 sec pbar at 8 GeV

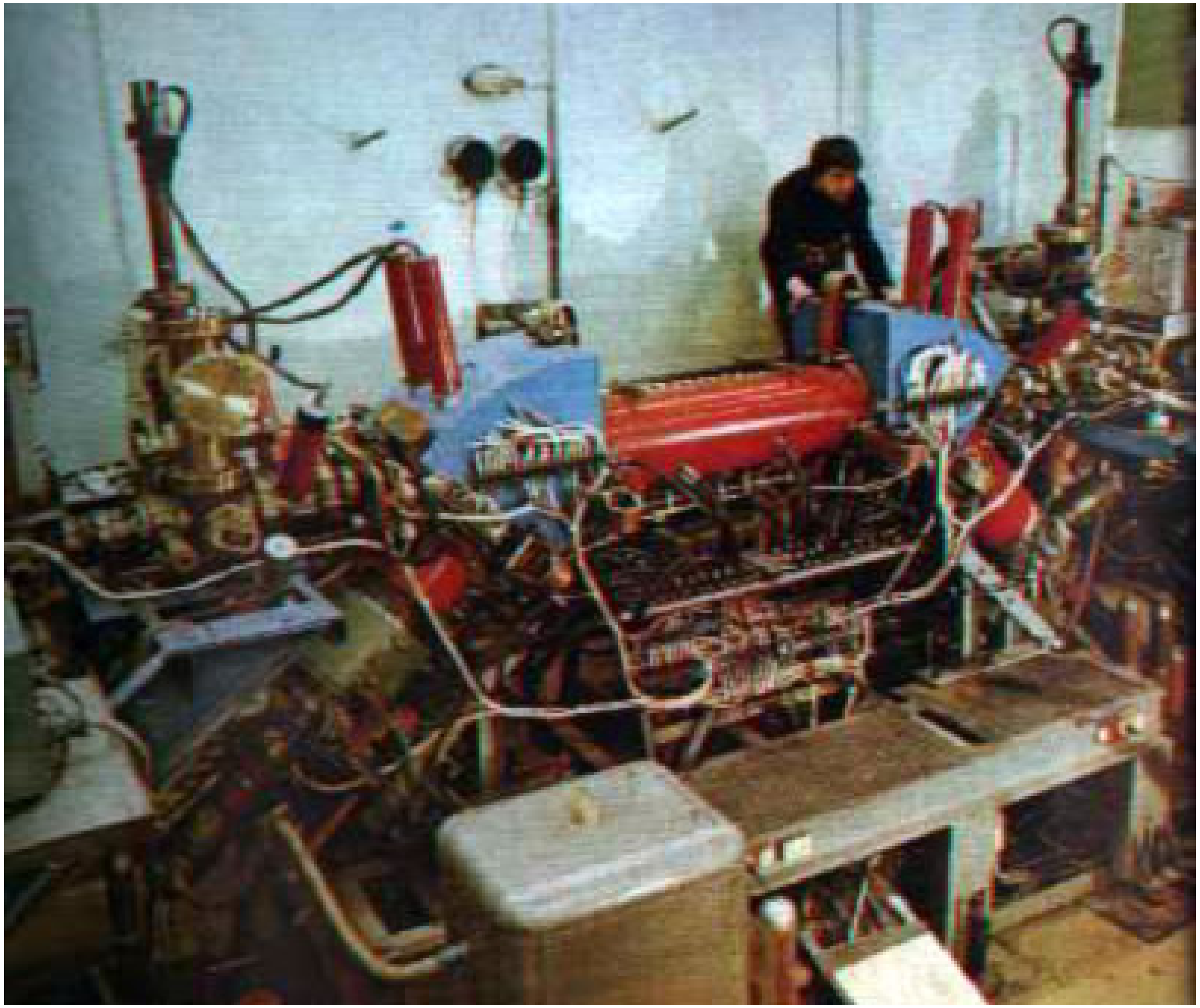


Electron cooling





Electron Cooling

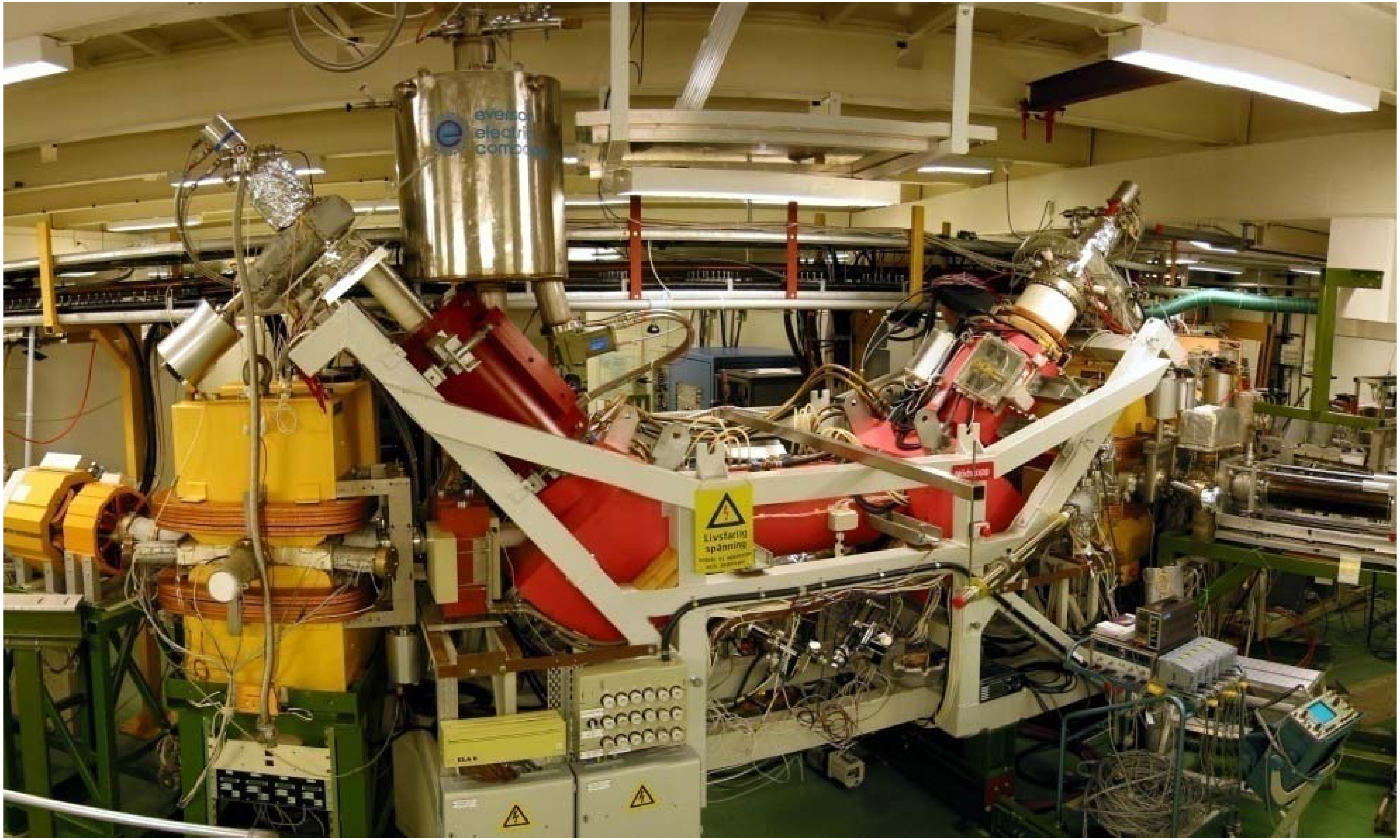


Invented by
Budker in
Novosibirsk

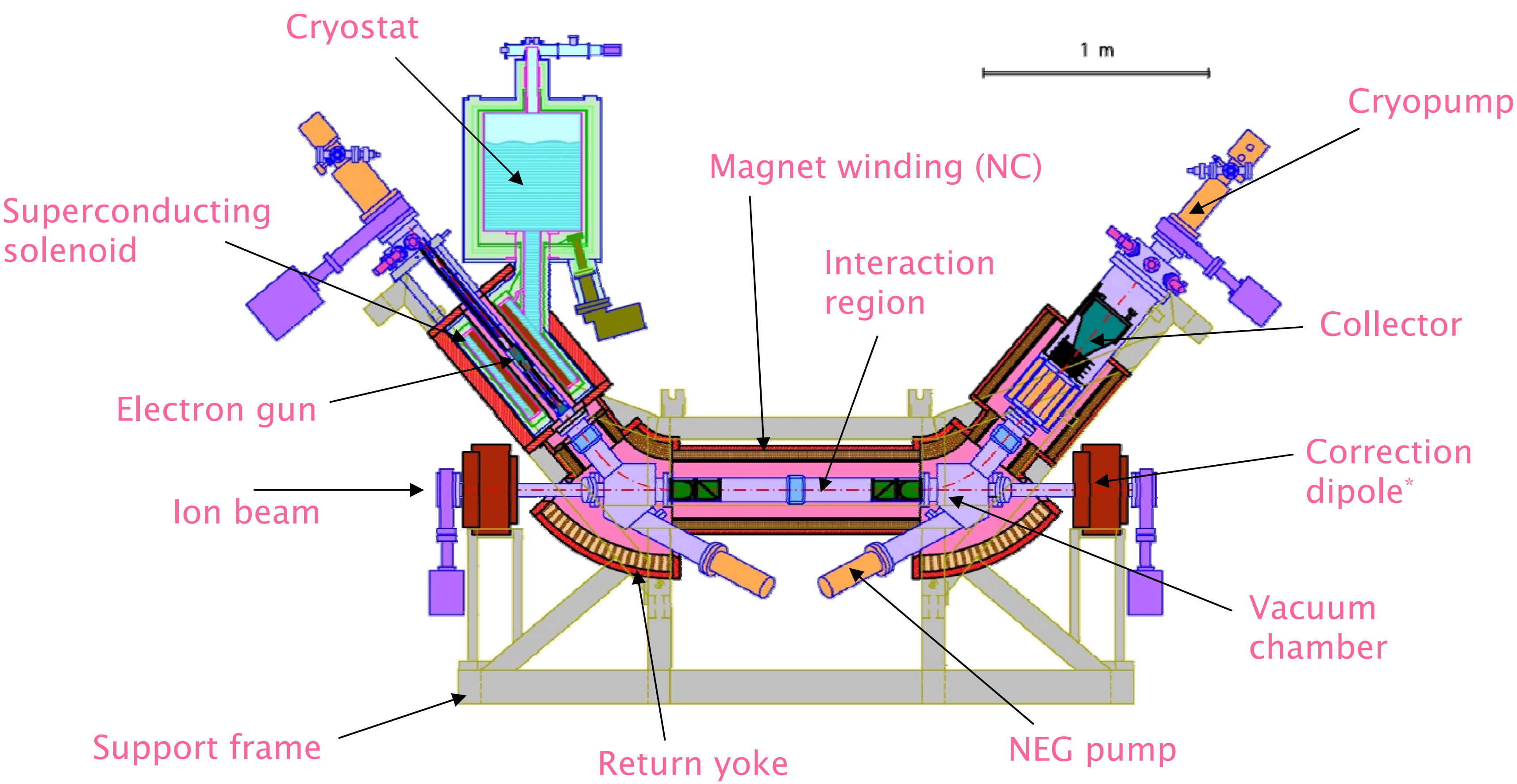
NAP-M ring
at INP, 1974,
68 MeV p

magnets:
solenoids
toroids

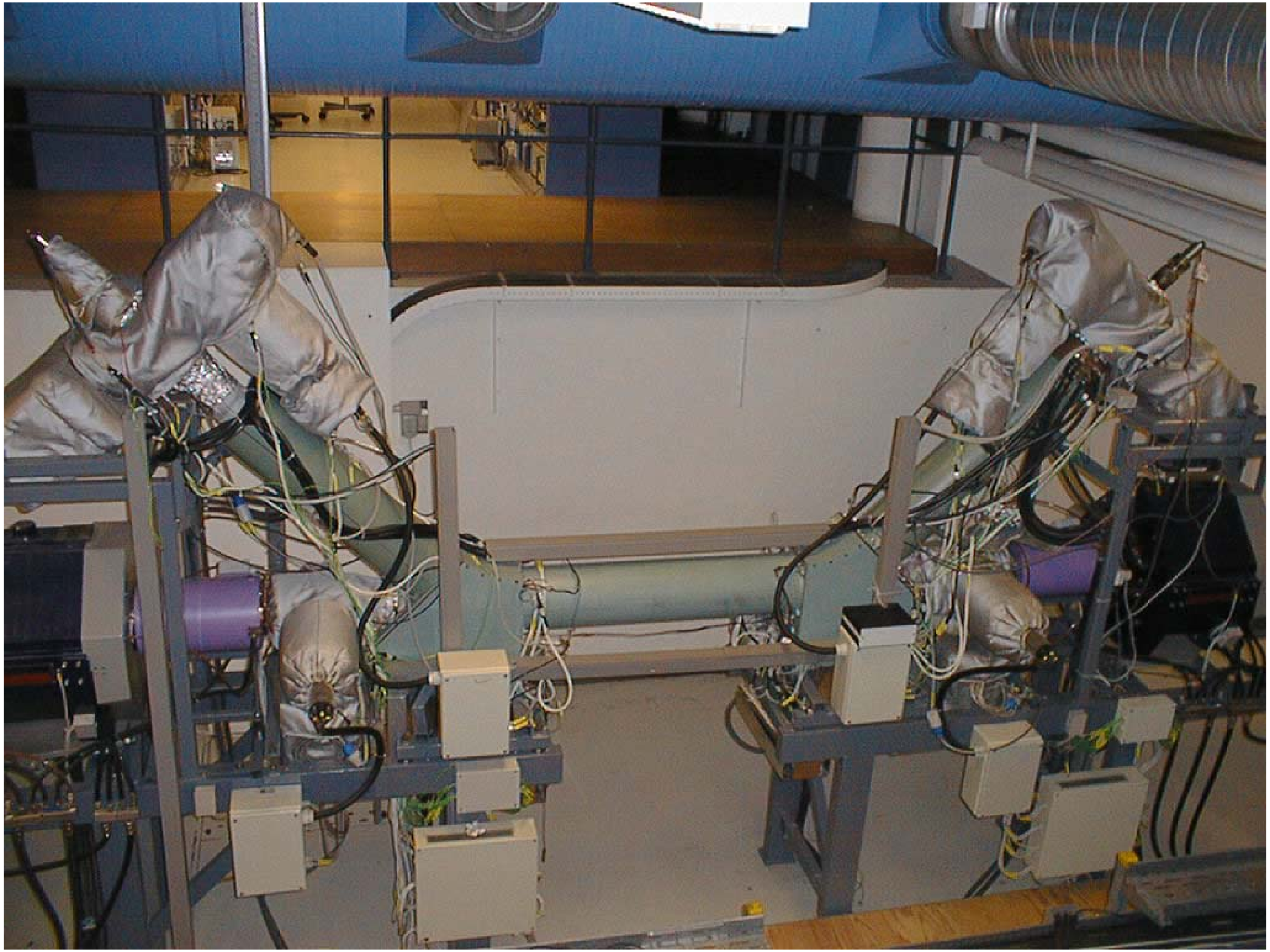
MSL in Stockholm



MSL electron cooler



ASTRID electron cooler



Electron cooling 2

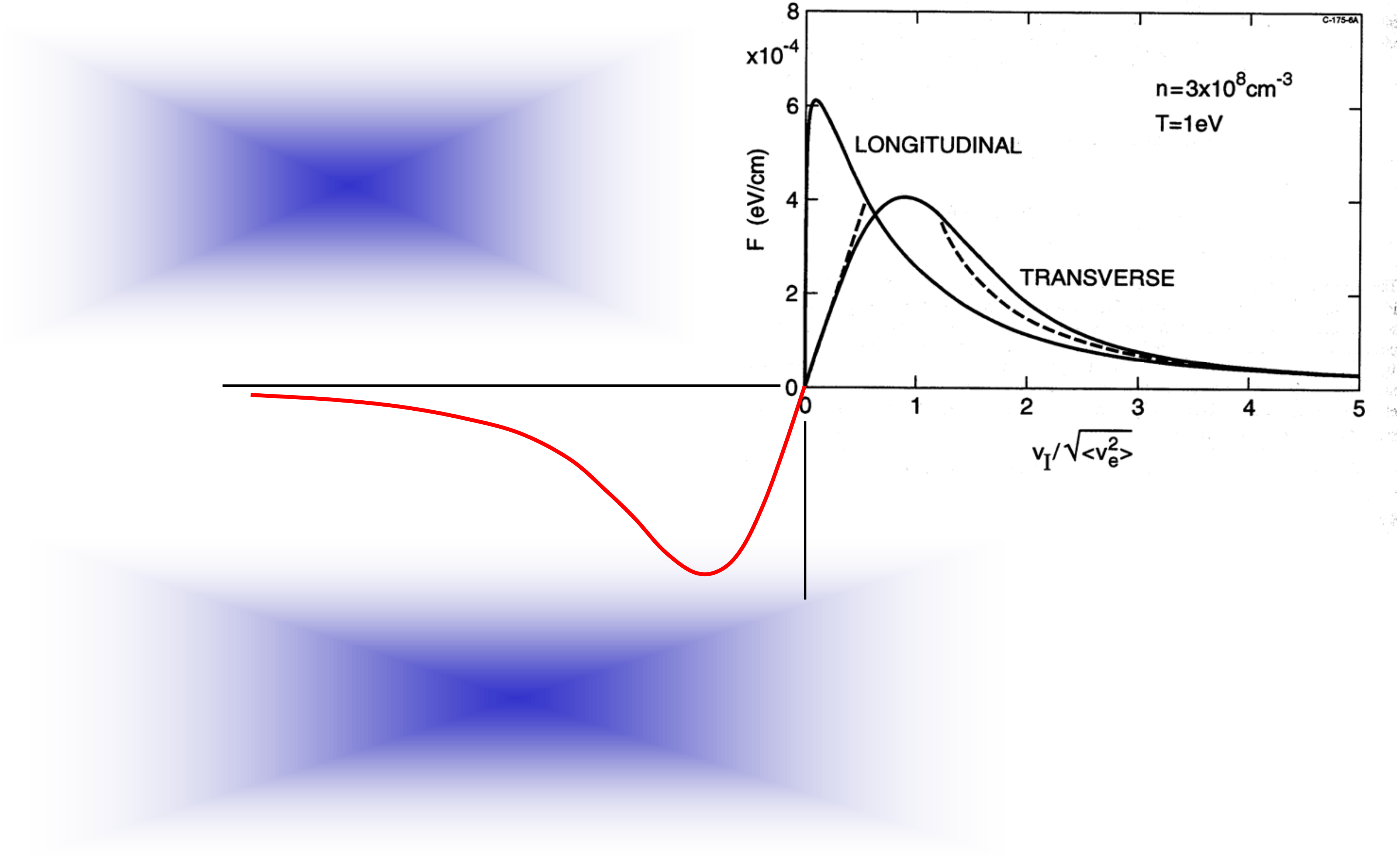
Initially $\overline{v_I^2} \geq \overline{v_e^2}$

$$T_I^i \equiv \frac{1}{2} M \overline{v_I^2} >> \frac{1}{2} m \overline{v_e^2} \equiv T_e^i$$

Finally $T_I^f = T_e^f$ no heating

$$v_I^{rms} \equiv \sqrt{\overline{v_I^2}} = \sqrt{\frac{m}{M}} v_e^{rms} \approx \frac{1}{43} \sqrt{\frac{m}{M}} v_e^{rms}$$

Electron cooling drag force



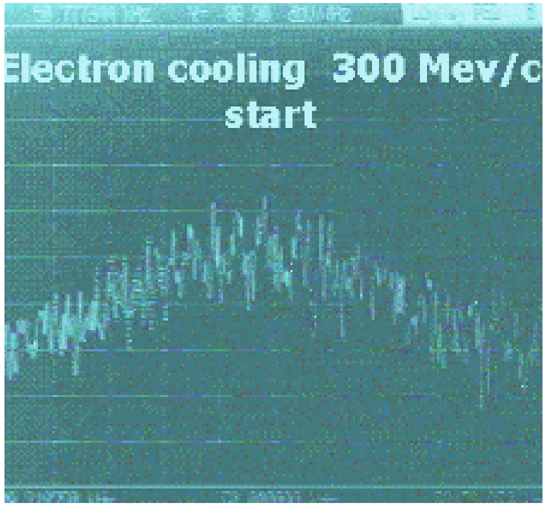
Electron cooling time

$$\tau \equiv \left| \frac{1}{v_I} \frac{dv_I}{dt} \right|^{-1} = \left| \frac{Mv_I}{F} \right|$$

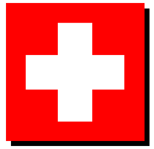
$$\tau = \frac{\gamma^2}{\eta} \frac{Mm}{Z^2 e^4} \frac{1}{nL} \begin{cases} \frac{1}{4\pi} (v_I^{PF})^3 & (v_I > v_e^{rms})^{PF} \\ \frac{3}{2\sqrt{2\pi}} \left(\frac{T_e}{m} \right)^{3/2} & (v_I < v_e^{rms})^{PF} \end{cases}$$

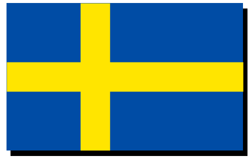
Typically τ~tens of seconds (Z=1)

Electron cooling

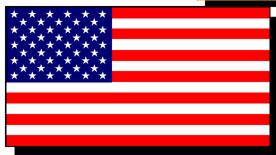


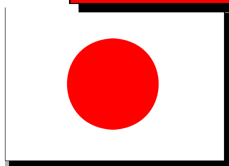
Electron cooling at AD

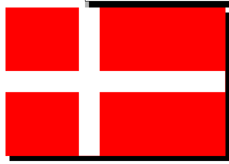
LEAR, ICE, AD @ CERN 

CRYRING, CELSIUS 

TSR, COSY, SIS, ESR 

IUCF, Fermilab 

TARN, .. 

ASTRID 

Mod. to simple description

1) Flattened distribution due to acceleration

$$T_{//} \approx 0 \Rightarrow \tau_{//} \downarrow$$

2)

$$B \neq 0 (B = \infty) \rightarrow T_{\perp} \approx 0 \rightarrow \tau_{\perp} \downarrow (\tau_{\perp} \propto v_I^{-3})$$

In practice B=∞ only for distant collisions

Virtues of electron cooling

Versatile cooling technique

Longitudinal and transverse cooling

Cooling times $\tau \approx 0.1\text{-}1 \sec A/Q^2$

$T_{//} << 0.1$ eV

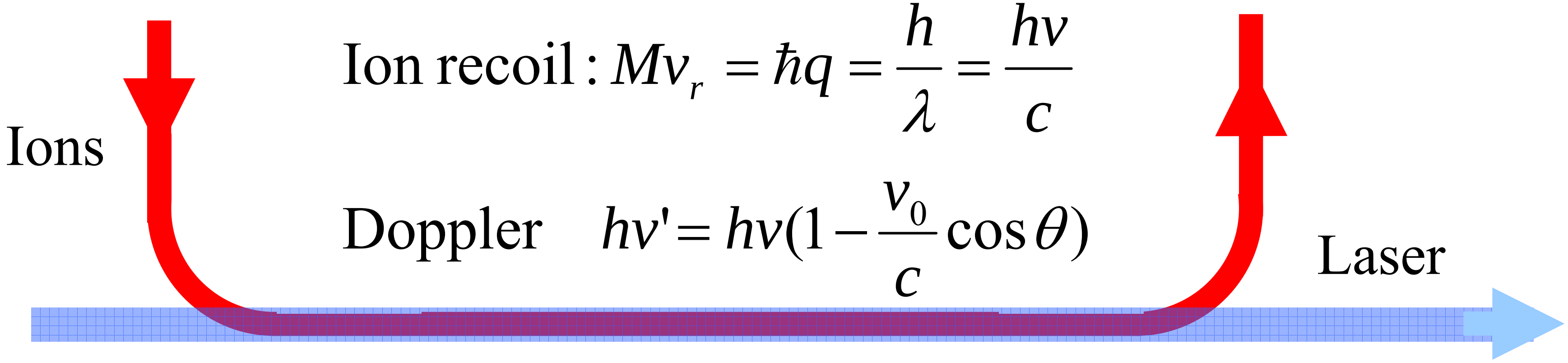
$T_{\perp} \approx 0.1$ eV

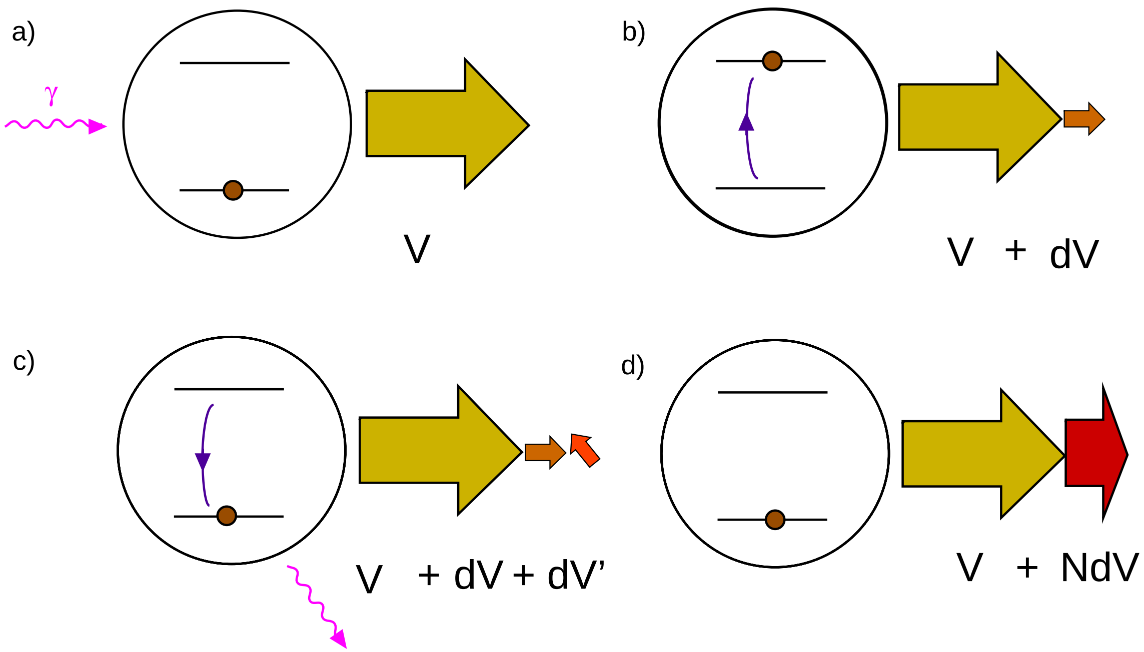
in addition: adiabatic expansion $T_{//} \propto B$

Laser cooling

$$\text{Ion recoil}: Mv_r = \hbar q = \frac{h}{\lambda} = \frac{h\nu}{c}$$

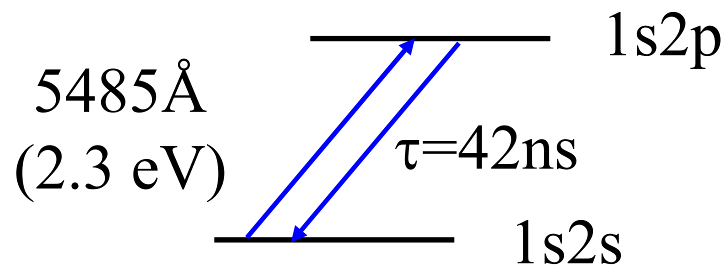
$$\text{Doppler} \quad h\nu' = h\nu\left(1 - \frac{v_0}{c}\cos\theta\right)$$





Kick from one photon absorption-emission

100 keV Li^+



Change in momentum : $\overline{\Delta p} = h / \lambda$

Change in energy : $\Delta E = p\Delta v = 12\text{meV}$

At saturation (stimulated = spontaneous)(1mW in Ø3mm)

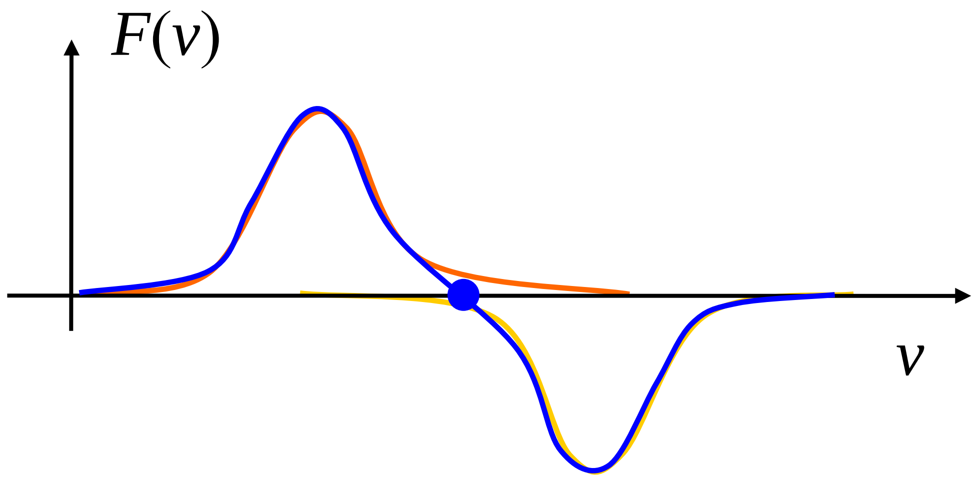
$r = \frac{1}{2}\Gamma = 10^7 \text{ s}^{-1}$

in 2 m : $r \cdot 2\text{m}/v = 15$

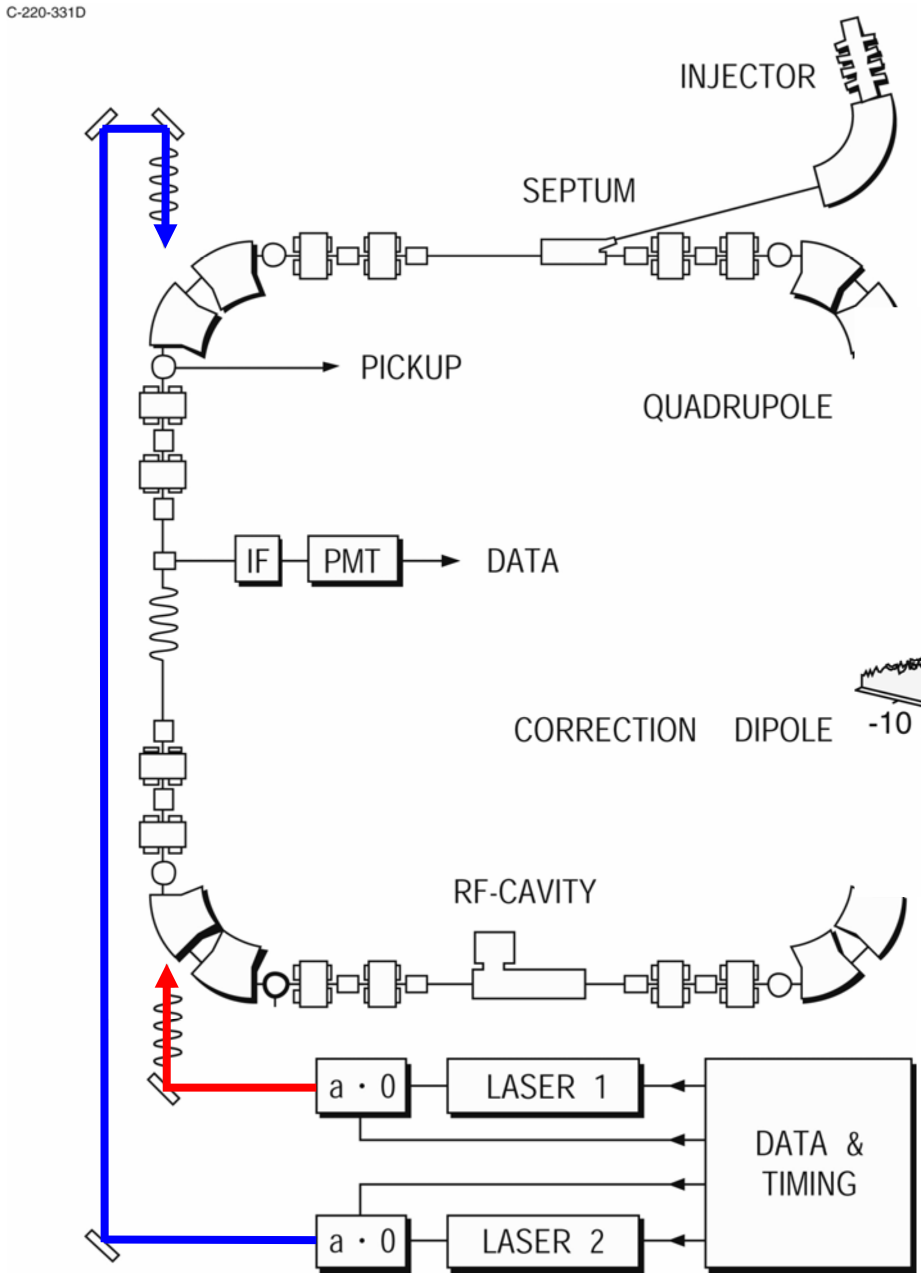
change in 2 m : 0.2 eV

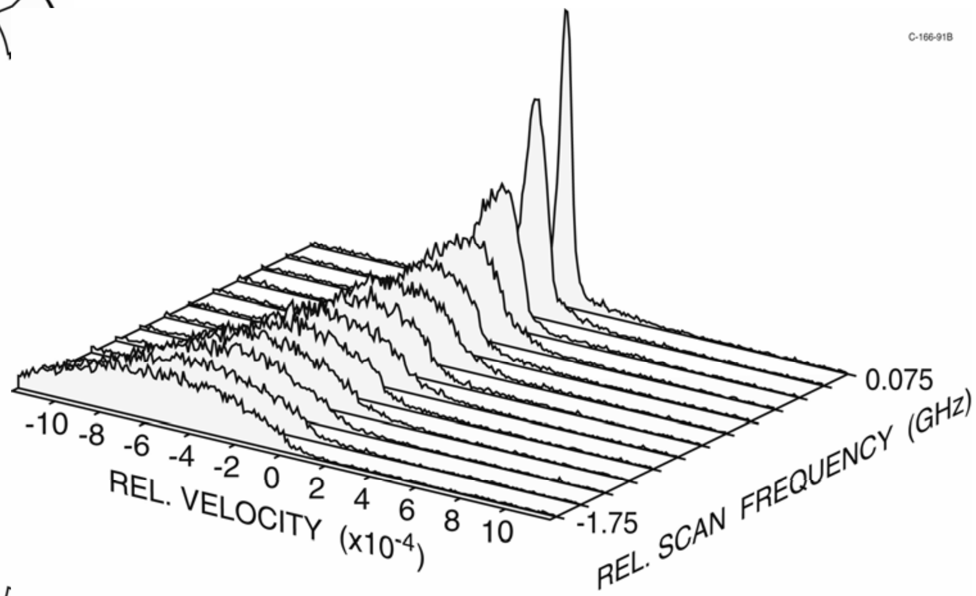
Ultimate limit : single recoil = 12meV

Laser cooling



Laser cooling in ASTRID





Laser cooling

Virtues of laser cooling:

Laser cooling is fast

However:

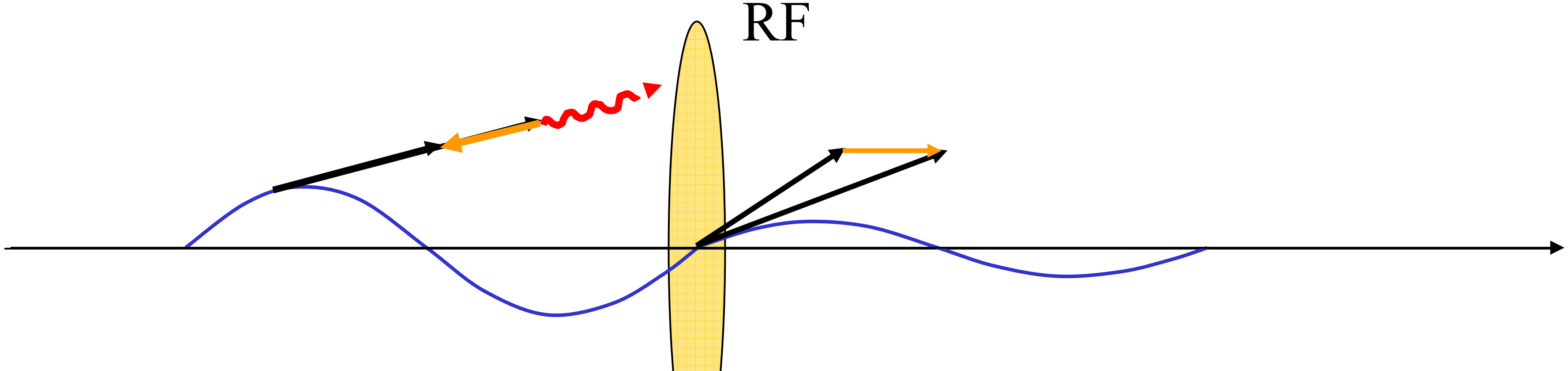
Only effective for longitudinal cooling

Not versatile: Li^+, Be^+, Mg^+, …

Radiation damping

(for details,
see lectures by L. Rivkin)

In principle: any charged particle
in practise: only electrons/positrons
since $\tau \approx E/(U_0/T_0)$



Vertical betatron cooling
Horisontal: dispersion!
Longitudinal: finite energy quanta

Ionisation cooling

Slowing down in matter
Friction force $\vec{F} \propto -\vec{v}$
Not hadrons due to large inelastic cross section
Not electrons due to short radiation length

Can only be used for in μ in μ-collider/ ν-factory

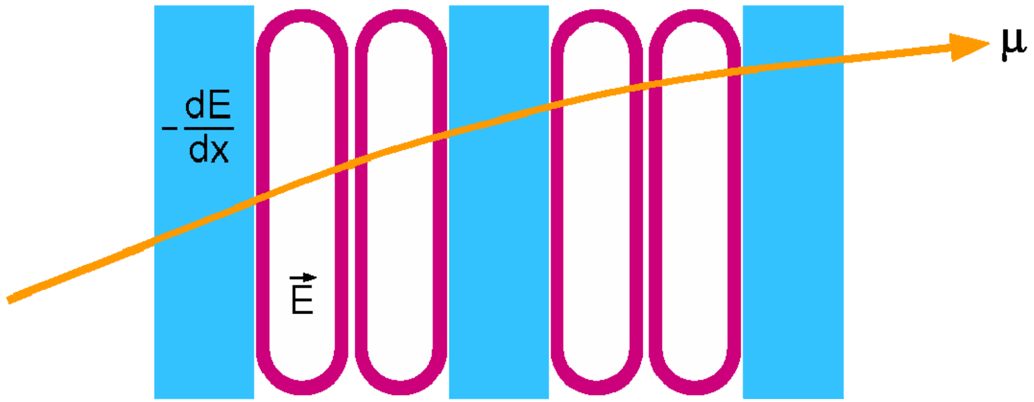
ν's produced by decaying μ's
μ's produced from decaying π's
π's produced by p's on target

Since μ's do not live forever (τ_0=2.2 μs)
cooling has to be fast (even when γ is large: $\tau = \gamma\tau_0$.

Also emittances are very large!

Ionisation cooling principle

Transverse cooling:
muons lose energy by dE/dx and longitudinal momentum is restored by RF

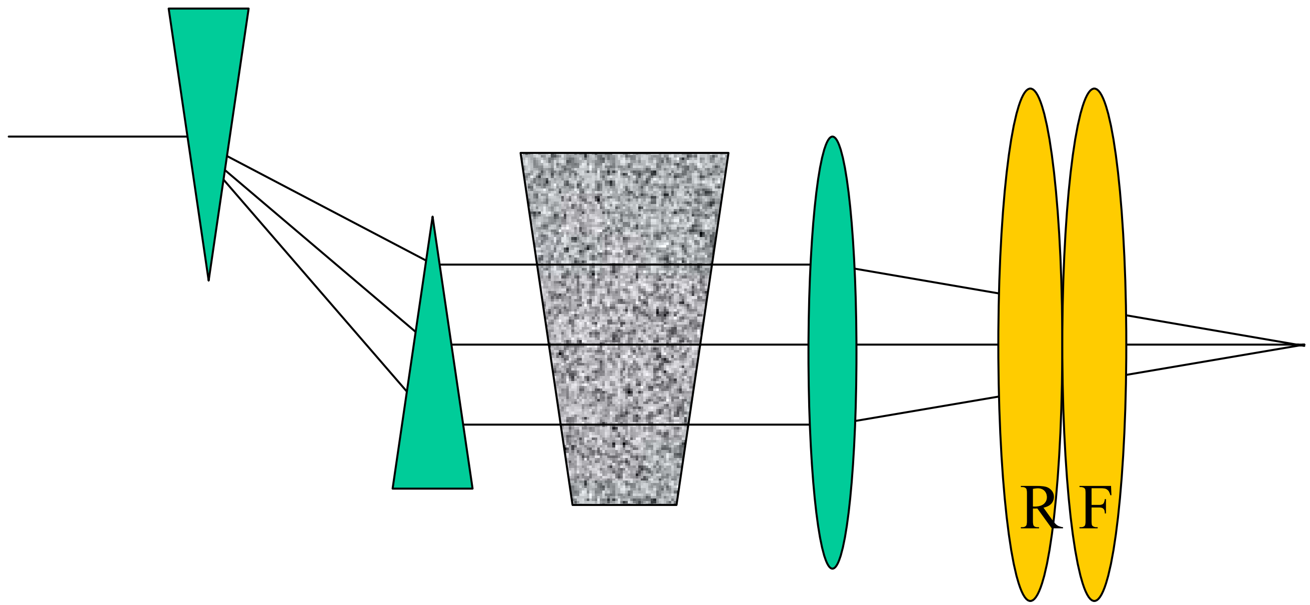


To minimize heating from Coulomb scattering:

- Small $\beta_\perp$ (high-field solenoids)
- Large L_R (low-Z absorber): Liquid H_2

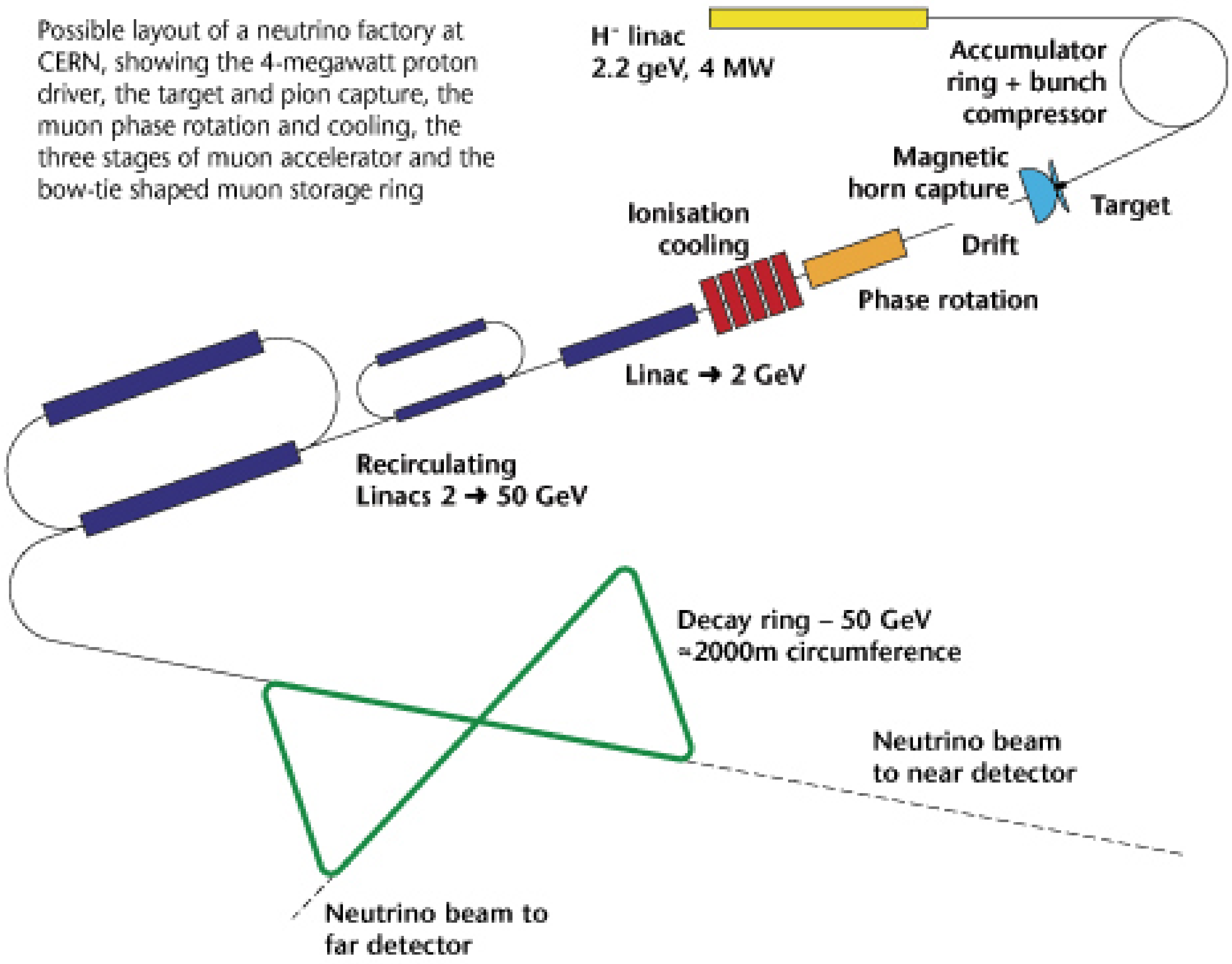
Ionisation energy cooling

Ionisation energy cooling using a wedge and dispersion

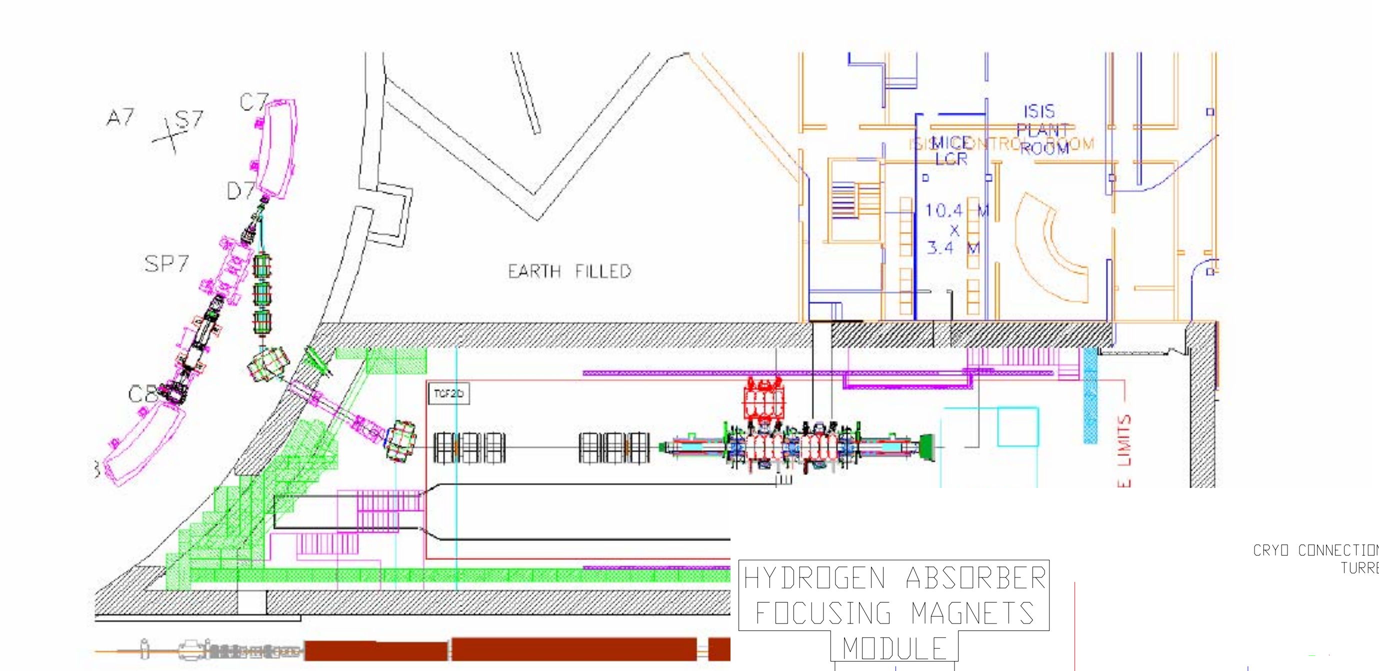


possible ν-factory at CERN

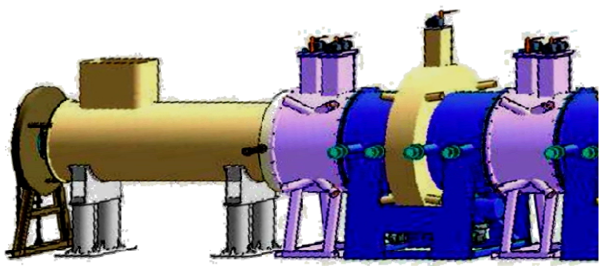
Possible layout of a neutrino factory at CERN, showing the 4-megawatt proton driver, the target and pion capture, the muon phase rotation and cooling, the three stages of muon accelerator and the bow-tie shaped muon storage ring

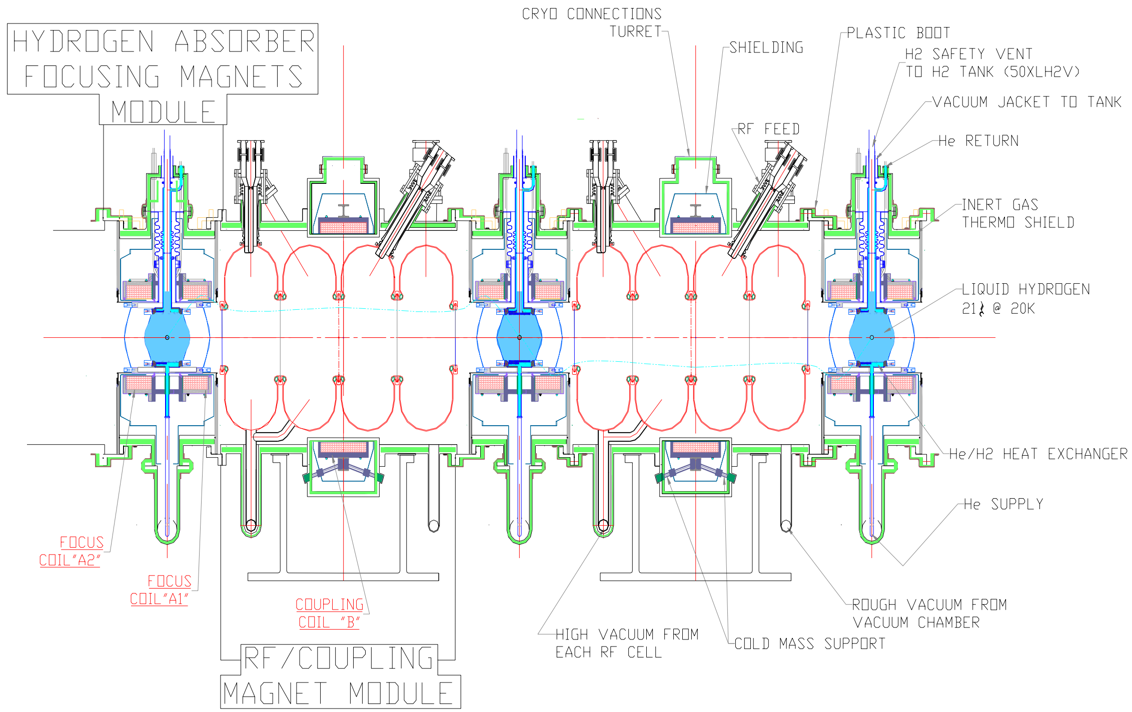


MICE at RAL



A7
S7
C7
D7
SP7
EARTH FILLED
ISIS PLANT ROOM
MICE LCR
10.4 M X 3.4 M



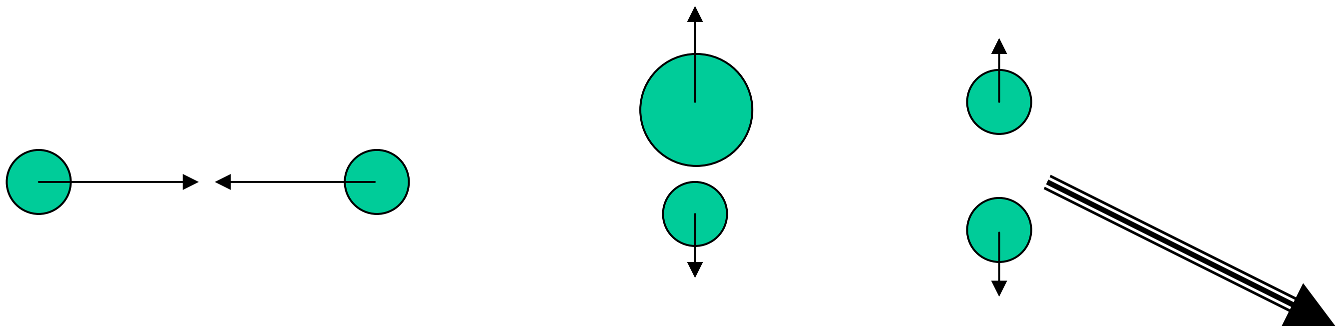


HYDROGEN ABSORBER FOCUSING MAGNETS MODULE
CRYO CONNECTIONS TURRET
SHIELDING
PLASTIC BOOT
H2 SAFETY VENT TO H2 TANK (50XLH2V)
VACUUM JACKET TO TANK
RF FEED
He RETURN
INERT GAS THERMO SHIELD
LIQUID HYDROGEN 21ℓ @ 20K
He/H2 HEAT EXCHANGER
He SUPPLY
ROUGH VACUUM FROM VACUUM CHAMBER
COLD MASS SUPPORT
HIGH VACUUM FROM EACH RF CELL
FOCUS COIL "A2"
FOCUS COIL "A1"
COUPLING COIL "B"
RF/COUPLING MAGNET MODULE

Other cooling methods

Stimulated radiation cooling

Radiative cooling



Conclusions

	Stochastic	Electron	Radiation	Laser	Ionisation
Species	all	ions	e^-/e^+	some ions	muons
Favoured beam velocity	high	medium $0.01<\beta$ $\beta<0.1$	very high $\gamma>100$	any (but Doppler)	any
Favoured beam intensity	low	any	any	any	any
Cooling time	$N \cdot 10^{-8}$ s	$10\text{-}10^{-2}$ s	$>10^{-3}$ s	$10^{-4}\text{-}10^{-5}$ s	10^{-6} s
Favoured beam temperature	high	low	any	low	any